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URBAN AIRSPACE DESIGN FOR AUTONOMOUS DRONE DELIVERY

Urban Airspace Design for Autonomous Drone Delivery

Proefschrift

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door

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SUMMARY

The paradigm of large-scale adoption of autonomous drone delivery promises to provide commercial and societal benefits. Over the past years, several companies have investigated the use-case of drones to transport small express packages of fast-food meals and time-sensitive medical supplies. The latter has shown to be highly beneficial in many parts of the world where traditional transport infrastructure remains largely non-existent. However, it is assumed that the true value of autonomous delivery drones can only be demonstrated when it is applied to urban environments. For example, the use of a large-scale fleet of autonomous drones to transport packages within the last-mile segment could potentially improve the economics of package delivery, reduce traffic congestion and help decrease the total anthropogenic carbon dioxide emissions in cities. In addition, supplementing the existing last-mile delivery system with this new technology could also help accelerate the European Union's 2050 vision of de-carbonising the transport sector. Autonomous drone delivery is obviously not a panacea to the above problems. It could, however, offer a path to mitigate such societal problems. Yet, even though there is a compelling case for autonomous drone delivery, it still remains to be deployed in cities. The reasons for this slow adoption include a large number of complex regulatory hurdles that vary between countries and cities. However, the biggest challenge is how to safely harbour large traffic volumes of drones in a constrained urban environment.

This thesis frames the scientific problem and outlines two main past research areas: unconstrained airspace design and road-based design, which served as a rich source of inspiration for this research. In a past study, known as the Metropolis project, it was demonstrated that layering the airspace and allocating flights to different altitude layers with respect to travel directions helped to mitigate the conflict probability in an unconstrained airspace setting. The study revealed two factors that were largely responsible for increasing the level of airspace safety, namely, segmentation of traffic and reduction of the relative speed, by traffic alignment, between cruising traffic at the same altitude. Furthermore, existing road vehicles, especially automated cars, provide an informative comparison with autonomous drones. Both emerging transportation modes are expected to navigate in constrained urban settings and operate in high traffic density scenarios. Of course, there are notable differences, for example, drones will operate in a three-dimensional space and the current performance limits of drones imply that it would not be optimal for drones to come to a sudden halt at intersections unlike cars and thus separating opposing traffic flows at intersections will be a difficult task. Yet, road design and research has evolved alongside road vehicles to include a host of safety measures in effort to make roads and streets safer for all its users. They make use of various conflict prevention measures to structure and organise traffic flows. Current roads and streets have channelisation planes, which help separate opposite flows of traffic using road markings, islands and raised medians to distinguish and support one-way and two-way streets. These forms of structuring have shown to reduce of the risks of conflicts and, to an extent, are able to safely harbour high traffic densities in highly constrained urban environments. The work in this thesis therefore aimed to investigate what design paradigms and methodologies from unconstrained airspace research and road infrastructure design can be translated to a constrained urban airspace for high-density drone traffic operations.

Before designing any infrastructure, we first need to estimate the expected traffic demand of autonomous drone delivery for an urban environment. There exist wide speculations with regard to the projected demand for drone delivery of small express packages and fast-food meals. Due to inconsistencies in the factors employed to project the traffic demand, the estimates can vary largely. This thesis defined the key factors that influence the traffic demand estimation statistics and proposed a coherent framework to compute the potential traffic demand and the traffic density for autonomous drone delivery of small express packages and fast-food meals for a typical city. In addition, a detailed case-study is presented to determine the traffic density of drone delivery for Paris metropolitan area. To analyse the feasibility of autonomous drone delivery from a user's perspective, the thesis discussed and compared the potential of fast-food meal delivery with respect to traditional delivery modes, such as a fleet of electric bicycles for Paris. The results of the developed traffic demand framework, indicated that the hourly traffic densities for autonomous drone delivery could potentially exceed the global commercial aircraft of 10,000 flights per day in 2019 by more than six-fold in just one potential city. The research in this thesis also presented a discussion of the challenges that need to be addressed by policymakers and designers of advanced mobility programs, such as U-Space. The discussion points towards the need for a radically new urban airspace in a way to facilitate large-scale drone delivery missions in dense cities.

Next, in an effort to safely harbour high traffic densities of autonomous delivery drones in a constrained urban environment, the research in this thesis presented a novel implementation of two airspace concepts. By leveraging the research in unconstrained airspace design and road design, we investigate the application of traffic segmentation and alignment to mitigate conflict probability. The research proposed two urban airspace concepts. The concepts bear resemblance to that of road-based design and thus consist of two-way and one-way streets by imposing horizontal constraints. Both concepts feature heading-altitude rules to vertically segment cruising traffic with respect to their travel direction. In addition, the airspace configurations contain transition altitudes to accommodate turning flights that need to decelerate and safely perform turns at intersections. For applicability, the two-way and one-way airspace concepts are applied to the urban street network of Manhattan, New York. Then after conducting fast-time simulation experiments in the open-source air traffic simulator, BlueSky, the performance of the concepts was compared and evaluated for multiple traffic densities in terms of safety, stability and efficiency. Note that that the concepts employed a state-based conflict detection algorithm, which linearly extrapolates the aircraft states to predict potential conflicts and losses of separation. Meanwhile, any conflicts that are detected are resolved in a pairwise manner using a speed-based tactical conflict resolution algorithm. The results suggest the concept with one-way traffic flow has better safety performance than the two-way traffic flow concept. More broadly, the analysis indicated that an effective way to structure drone traffic in a constrained urban setting is to have vertically segmented altitude layers with respect to travel directions and horizontal constraints to enforce unidirectional traffic flow.

To understand the intricate differences between the two urban airspace concepts, this thesis explored and analysed the salient conflict properties. Using fast-time simulations, the different types of conflicts are captured and analysed for multiple traffic demand scenarios. The results suggest that conflicts are largely caused by flights that are either climbing or descending to their respective altitude layers. Such merging conflicts occur mainly because of the introduction of transition altitude layers that accommodate turning traffic and thus prevent any interruption to the through-traffic flow. These merging conflicts need to be managed and circumvented.

The airspace design concepts proposed in this thesis consist of rules and interventions to safely facilitate large-scale drone traffic in a constrained urban environment. More specifically, the heading-altitude rule and the spatial order of the urban street network is used to impose traffic segmentation and alignment. As a consequence, this required drones to climb and descend to their respective altitudes and thus triggering merging conflicts. To mitigate the merging conflicts and losses of separation that arise when transitioning between altitude layers, the research in thesis proposed two merge-assisting strategies that are broadly used in road traffic research. The merge assistance employed a delay-based and speed-based strategy to prevent and thus reduce the onset of merging conflicts and losses of separation. To evaluate their performance, the merge assistance strategies are applied to the one-way airspace concept and simulations are performed across three traffic demand scenarios for the urban street network of

Manhattan, New York. The simulation results demonstrated that the merge assistance policies were able to decrease the number of losses of separation for merging flights. But, the results of the merge assistance strategies were shown to be less effective than what was initially hypothesised. To determine the cause for this relatively low efficacy of the merge-assisting strategies, the mesoscopic features of the urban street network were examined. The data indicated that the relatively low efficacy of the merge-assisting policies were caused by insufficient space for safe manoeuvrability and the inability of the policies to fully respond and thus resolve any merging conflicts on short-distance streets.

The research enclosed in this thesis represents a first exploratory steps to structure and organise a constrained urban environment for high-density delivery drone traffic. As a result, a number of assumptions have been employed to reduce the complexity of the simulations. For example, one of the assumptions is the use of a decentralised tactical separation method. This thesis discussed the potential of also considering centralised capacity management together with decentralised control, which is somewhat similar to how conflict management is orchestrated in road traffic.

The work in this thesis focused on the application of safely accommodating high densities of autonomous delivery drones in a constrained urban environment that featured an orthogonal street network. In addition, the methods and insights proposed in this thesis could also be applied to other constrained settings, including in-door environments, for example, in mega-scale warehouses and manufacturing plants to support the transport of packages via a fleet of autonomous drones. Moreover, the research presented in this thesis could also be applicable towards other advanced air mobility concepts, such as passenger drones or flying taxis.

The use of autonomous drones to transport packages, or people, is an eminently practical approach that is receiving large amounts of financial investment. It is likely that the technology will need to deliver the assumed returns on investment at some point in time. However, before such advanced air mobility concepts move from theory to practice, the policy frameworks, public acceptance and trust, and the technical feasibility need to be urgently addressed by ethically responsible policymakers and designers.

SAMENVATTING

Het paradigma van grootschalige toepassing van autonome dronebezorging belooft commerciële en maatschappelijke voordelen op te leveren. In de afgelopen jaren hebben verschillende bedrijven onderzoek gedaan naar het gebruik van drones voor het vervoer van kleine exprespakketten fastfoodmaaltijden en tijdgevoelige medische benodigdheden. Dit laatste is zeer nuttig gebleken in vele delen van de wereld waar de traditionele vervoersinfrastructuur nog grotendeels niet bestaand is. Aangenomen wordt echter dat de werkelijke waarde van autonome bezorgdrones pas kan worden aangetoond wanneer zij worden toegepast in stedelijke omgevingen. Zo zou het gebruik van een grootschalige vloot autonome drones voor het vervoer van pakketten in het 'last mile' segment de rendabiliteit van pakketbezorging kunnen verbeteren, de verkeerscongestie kunnen verminderen en de totale antropogene kooldioxide-uitstoot in steden kunnen helpen verminderen. Bovendien zou het aanvullen van het bestaande systeem van 'last mile delivery' met deze nieuwe technologie ook kunnen helpen om de visie van de Europese Unie voor 2050 om de transportsector koolstofvrij te maken, te versnellen. Autonome bezorging met drones is uiteraard geen wondermiddel voor de bovengenoemde problemen. Het zou echter wel een manier kunnen zijn om dergelijke maatschappelijke problemen te verminderen. Maar ook al zijn er overtuigende argumenten voor autonome drone bezorging, toch wordt het nog steeds niet in steden toegepast. De redenen voor deze trage adoptie zijn onder meer een groot aantal complexe regelgevingshindernissen die per land en stad verschillen. De grootste uitdaging is echter hoe grote hoeveelheden drones zich veilig laten te bewegen in een beperkte stedelijke omgeving.

Deze dissertatie kadert het wetenschappelijke probleem en schetst twee belangrijke vroegere onderzoeksgebieden: onbelemmerd luchtruimontwerp en wegontwerp, die een rijke bron van inspiratie vormden voor dit onderzoek. In een eerdere studie, bekend als het Metropolis project, werd aangetoond dat gelaagdheid van het luchtruim en het toewijzen van vluchten aan verschillende hoogtelagen met betrekking tot reisrichtingen, hielp om de conflictkans in een ongedeelde luchtruimsetting te beperken. Daaruit kwamen twee factoren naar voren die in hoge mate verantwoordelijk waren voor het verhogen van het veiligheidsniveau in het luchtruim, namelijk segmentering van het verkeer en vermindering van de relatieve snelheid, door verkeersafstemming, tussen kruisend verkeer op dezelfde hoogte. Bestaande wegvoertuigen, met name automatische auto's, vormen bovendien een informatieve vergelijking met autonome drones. Van beide opkomende vervoerswijzen wordt verwacht dat ze navigeren in een beperkte stedelijke omgeving en opereren in scenario's met een hoge verkeersdichtheid. Natuurlijk zijn er opmerkelijke verschillen: drones zullen bijvoorbeeld in een driedimensionale

ruimte opereren en de huidige prestatielimieten van drones impliceren dat het voor drones niet optimaal zou zijn om plotseling tot stilstand te komen op kruispunten, in tegenstelling tot auto's. Het scheiden van tegengestelde verkeersstromen op kruispunten zal dus een moeilijke taak zijn. Het ontwerp van en onderzoek naar wegen is echter samen met wegvoertuigen geëvolueerd en omvat een hele reeks veiligheidsmaatregelen om wegen en straten veiliger te maken voor alle weggebruikers. Zij maken gebruik van verschillende conflictpreventiemaatregelen om de verkeersstromen te structureren en te organiseren. De huidige wegen en straten zijn verdeeld in vlakken vergelijkbaar met kanalen, die helpen om tegengestelde verkeersstromen te scheiden door middel van wegmarkeringen, eilanden en verhoogde middenbermen om eenrichtings- en tweerichtingsstraten te onderscheiden en te ondersteunen. Deze vormen van structurering hebben aangetoond de risico's van conflicten te verminderen en zijn, tot op zekere hoogte, in staat om veilig hoge verkeersdichtheden te huisvesten in zeer beperkte stedelijke omgevingen. Het doel van dit proefschrift is te onderzoeken welke ontwerpparadigma's en methodologieën uit onderzoek naar niet-beperkt luchtruimen en de ontwerpen van weginfrastructuur, kunnen worden vertaald naar een beperkt stedelijk luchtruim voor droneverkeer met hoge dichtheid.

Alvorens het ontwerpen van een infrastructuur, moeten we eerst een inschatting maken van de verwachte verkeersvraag van autonome drone bezorging voor een stedelijke omgeving. Brede speculaties bestaan met betrekking tot de verwachte vraag naar drone bezorging van kleine exprespakketten en fast-food maaltijden. Als gevolg van inconsistenties in de factoren die worden gebruikt om de verkeersvraag te projecteren, kunnen de schattingen sterk variëren. Deze dissertatie definieert de belangrijkste factoren die de schattingsstatistieken van de verkeersvraag beïnvloeden en stelt een coherent raamwerk voor om de potentiële verkeersvraag en de verkeersdichtheid te berekenen voor autonome drone bezorging van kleine exprespakketten en fast-food maaltijden voor een typische stad. Daarnaast wordt een gedetailleerde case studie gepresenteerd om de verkeersdichtheid van drone bezorging voor het Parijse Metropol gebied te bepalen. Om de haalbaarheid van autonome bezorging met drones vanuit het perspectief van de gebruiker te analyseren, wordt in de dissertatie het potentieel van bezorging van fast-food maaltijden besproken en vergeleken met traditionele bezorgmethoden, zoals een vloot van elektrische fietsen voor Parijs. De resultaten van het ontwikkelde verkeersvraagkader gaven aan dat de verkeersdichtheden per uur voor autonome dronebezorging potentieel het wereldwijde commerciële vluchtverkeer van 10.000 vluchten per dag in 2019, met meer dan het zesvoudige zouden kunnen overschrijden in slechts één potentiële stad. Het onderzoek in deze dissertatie presenteert ook een discussie over de uitdagingen die moeten worden aangepakt door beleidsmakers en ontwerpers van geavanceerde mobiliteitsprogramma's, zoals U-Space. De discussie wijst ons op de behoefte aan een radicaal nieuw stedelijk luchtruim om zo de grootschalige drone bezorgmissies in dichtbevolkte steden te faciliteren.

In een poging om hoge verkeersdichtheden van autonome bezorgdrones veilig te huisvesten in een beperkte stedelijke omgeving, presenteert het onderzoek in deze dissertatie een nieuwe implementatie van twee luchtruimconcepten. Door gebruik te maken van het onderzoek naar het ontwerp van niet-gecontroleerde luchtruimtes en het ontwerp van wegen, onderzochten we de toepassing van verkeerssegmentatie en -uitlijning om de kans op conflicten te verkleinen. Het onderzoek stelde twee stedelijke luchtruimconcepten voor. De concepten vertonen gelijkenis met die van wegontwerpen en bestaan dus uit tweerichtings- en eenrichtingsstraten, te realiseren door het opleggen van horizontale beperkingen. Beide concepten bevatten heading-altitude regels om kruisend verkeer verticaal te segmenteren ten opzichte van hun reisrichting. Bovendien bevatten de luchtruimconfiguraties overgangshoogtes om tegemoet te komen aan afslaande vluchten die moeten vertragen en veilig bochten moeten nemen op kruispunten. Om de toepasbaarheid te toetsen worden de luchtruimconcepten voor tweerichtings- en eenrichtingsverkeer toegepast op het stedelijke stratennetwerk van Manhattan, New York. Na het uitvoeren van simulatie-experimenten in de open-source luchtverkeersimulator BlueSky, werden de prestaties van de concepten vergeleken en geëvalueerd voor verschillende verkeersdichtheden in termen van veiligheid, stabiliteit en efficiëntie. Noemenswaardig is dat de concepten gebruik maakten van een toestand gebaseerd conflict detectie algoritme, dat de toestanden van de vliegtuigen lineair extrapoleert om potentiële conflicten en verlies van separatie te voorspellen. Ondertussen worden alle gedetecteerde conflicten paarsgewijs opgelost met behulp van een tactisch conflictoplossingsalgoritme op basis van snelheid. De resultaten wijzen erop dat het concept van eenrichtingsverkeer betere veiligheidsprestaties levert dan het concept van tweerichtingsverkeer. Meer in het algemeen geeft de analyse aan dat een effectieve manier om droneverkeer te structureren in een stedelijke omgeving met beperkingen bestaat uit verticaal gesegmenteerde hoogtelagen met betrekking tot reisrichtingen en horizontale beperkingen om eenrichtingsverkeer af te dwingen.

Om de complexe verschillen tussen de twee stedelijke luchtruimconcepten te begrijpen, zijn in deze dissertatie de belangrijkste conflicteigenschappen onderzocht en geanalyseerd. Met behulp van snelle simulaties zijn de verschillende soorten conflicten in beeld gebracht en geanalyseerd voor meerdere verkeersvraagscenario's. De resultaten suggereren dat conflicten grotendeels worden veroorzaakt door vluchten die ofwel klimmen ofwel dalen naar hun respectievelijke hoogtelagen. Dergelijke samenvoegingsconflicten ontstaan vooral door de invoering van overgangshoogtelagen die plaats bieden aan afslaand verkeer en zo onderbreking van de doorgaande verkeersstroom voorkomen. Deze samensvoegingsconflicten moeten worden beheerd en omzeild.

De luchtruimontwerp concepten die in deze dissertatie worden voorgesteld bestaan uit regels en interventies om grootschalig droneverkeer veilig te faciliteren in een beperkte stedelijke omgeving. Meer specifiek wordt de heading-altitude regel en de ruimtelijke orde van het stedelijke stratennetwerk gebruikt om verkeerssegmentatie en uitlijning op te leggen. Als gevolg hiervan moesten drones klimmen en dalen naar hun respectieve hoogtes en zo samenvoegingsconflicten uitlokken. Om de samenvoegingsconflicten en het verlies aan separatie te beperken, die ontstaan bij de overgang tussen hoogtelagen, stelt het onderzoek twee samenvoeghulpstrategieën die algemeen worden gebruikt in wegverkeersonderzoek voor. De samenvoegondersteuning maakte gebruik van een vertraging- en snelheid gebaseerde strategie om het ontstaan van samenvoegingsconflicten en om het verlies van separatie te voorkomen en dus te beperken. Om hun prestaties te evalueren, worden de samenvoeg ondersteuning strategieën toegepast op het luchtruimconcept met éénrichtingsverkeer en worden simulaties uitgevoerd over drie verkeersvraagscenario's voor het stedelijke stratennetwerk van Manhattan, New York. De simulatieresultaten tonen aan dat de beleidsmaatregelen voor samenvoeging ondersteuning het aantal separatieverliezen voor samenvoegende vluchten kan beperken. De resultaten van de samenvoeging ondersteuning strategieën bleken echter minder effectief te zijn dan aanvankelijk werd verondersteld. Om de oorzaak van deze relatief lage effectiviteit van deze strategieën te achterhalen, werden de mesoscopische kenmerken van het stedelijke stratennetwerk onderzocht. De gegevens wezen uit dat de relatief geringe effectiviteit van de invoegstrategieën werd veroorzaakt door onvoldoende ruimte voor veilige manoeuvreerbaarheid en het onvermogen van de beleidsmaatregelen om volledig te reageren en zo eventuele conflicten over het invoegen op straten met een korte afstand op te lossen.

Het onderzoek in deze dissertatie is een initieel verkennend onderzoek naar het structureren en organiseren van een beperkte stedelijke omgeving voor droneverkeer met hoge dichtheid. Als gevolg hiervan zijn een aantal aannames gehanteerd om de complexiteit van de simulaties te beperken. Een van de aannames is bijvoorbeeld het gebruik van een gedecentraliseerde tactische scheidingsmethode. Deze dissertatie besprak ook de mogelijkheid om gecentraliseerd capaciteitsmanagement te overwegen in combinatie met gedecentraliseerde controle, wat enigszins vergelijkbaar is met hoe conflictmanagement in het wegverkeer wordt georganiseerd.

Het werk in deze dissertatie richtte zich op de toepassing van het veilig accommoderen van hoge dichtheden van autonome leveringsdrones in een beperkte stedelijke omgeving met een orthogonaal stratennetwerk. Daarnaast kunnen de methoden en inzichten die in dit proefschrift worden voorgesteld ook worden toegepast op andere begrensde omgevingen, waaronder binnen ruimtes, bijvoorbeeld in grootschalige magazijnen en fabrieken om het vervoer van pakketten via een vloot van autonome drones te ondersteunen. Bovendien zou het onderzoek dat in dit proefschrift wordt gepresenteerd ook kunnen worden toegepast op andere geavanceerde luchtmobiliteitsconcepten, zoals passagiersdrones of vliegende taxi's.

Het gebruik van autonome drones voor het vervoer van pakketten, of mensen, is een bij uitstek praktische benadering waarin veel financiële investeringen worden gedaan. Het is waarschijnlijk dat de technologie op een bepaald moment het veronderstelde rendement op investering zal moeten opleveren. Voordat dergelijke geavanceerde luchtmobiliteitsconcepten echter van de theorie in de praktijk worden gebracht, moeten ethisch verantwoorde beleidsmakers en ontwerpers zich dringend buigen over de beleidskaders, de aanvaarding en het vertrouwen van het publiek, en de technische haalbaarheid.

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INTRODUCTION

Advanced air mobility concepts, such as flying taxis and delivery drones have already begun test-flights in urban environments. Such novel mobility scenarios are evolving and their technology offers a path towards zero-emissions transportation in urban settings. In this dissertation, we focus our research within the context of emerging drone-based delivery missions. In this chapter, we describe the essential background material for this research. Specifically, the problem is defined and four main research questions are established. Finally, the chapter gives an outline of the dissertation and provides a brief overview of each chapter.

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1.1. BACKGROUND

The rapid technological advancement of unmanned aerial vehicles (UAVs), also known as drones, has allowed for its novel applicability to be utilised in fields such as agriculture, research, surveillance disaster management and health care [34, 66, 70, 105, 118]. However, the most enticing use-case has been in the field of logistics, especially in the transport of small express packages and fast-food meals as well as time-sensitive medical supplies via a fleet of autonomous drones [69, 179].

This paradigm of drone delivery was first introduced in 2014 by the CEO of Amazon (a global e-commerce company) that captured widespread media attention and the allocation of financial resources for research and development to launch innovative start-ups [148, 175]. As a result, several companies such as Amazon Prime Air, Google Wing, Matternet and Flytrex have been experimenting with drones to deliver small commercial goods weighing less than 2.5 kg across a distance of 5 km under a time-frame of 30 min [62, 111]. A majority of these flight tests have been demonstrated in dense crowded urban environments [160].

Large multinational package delivery and supply chain management companies such as UPS (Figure 1.1) and Deutshe Post DHL have also been exploring the use of drones to deliver packages for the last-mile segment, that is, the segment between the distribution centre and the final destination. Similarly, quick service restaurants and food delivery platforms have also been experimenting with drones in order to deliver fast-food meal orders of customers living cities (see Figure 1.2) [111]. Most recently, a fleet of autonomous delivery drones were utilised for the purpose of swiftly transporting lightweight and critical medical supplies to hospitals in Zhejiang Province China in an effort to curtail the escalation of the coronavirus disease 2019 outbreak [136] (Figure 1.3).

The reasons for the growing interest and the increasing influx of investments in the novel transportation mode of drone-based delivery, especially in urban environments, are primarily driven by three major societal problems, namely, traffic congestion, anthropogenic carbon emissions and the economics of last-mile delivery, which are all largely intertwined [142, 179].

Globally, urban population is growing at a rate of 1.5 million people per week [152]. As urbanisation creates an array of opportunities for cities, it places increasing demands on existing urban infrastructure systems, transport networks, in particular, which ultimately leads to the onset of traffic congestion and gridlocks. Not only does traffic congestion affect wealthy and developed cities such as New York, London and Paris, it also cripples daily life in developing cities, such as Bogotá, Rio de Janeiro and Mexico city [61].

Figure 1.1: A modified copter drone carrying a lightweight package for UPS [81].

Figure 1.2: Modified DJI matrice 600 copter transporting fast food meals for Uber Eats, adopted from [111].

Figure 1.3: A copter drone transporting medical supplies to a hospital, adopted from [136].

Consequences of traffic congestion have been associated with serious economic costs as well as psychological implications [61]. In the USA alone, the cost of traffic congestion incurs a cost of USD 88 Billion per year, which translates to USD 1,400 per citizen [96]. Because a majority of the cities, particularly in the USA, are also experiencing urban sprawl, its urbanites are coerced to travel further to reach their destinations [16]. This ultimately results in nearly 100 hours per year per person of productive time expended by being stuck in traffic [96]. Traffic congestion and the rise of car ownership numbers not only have economic implications, but have also greatly contributed towards accelerating anthropogenic emissions.

Harmful vehicle emissions erode the quality of air, which triggers a cascade of respiratory and neurological health problems for urban occupants [211]. In

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addition, it is a predominant contributor of anthropogenic carbon emissions. Road transport alone accounts for nearly 12 percent of all anthropogenic carbon emissions [159], see Figure 1.4. From the latter estimate, almost 40 percent is attributed to delivery trucks and vans, for which more than 85 percent of the goods could be transported by a more efficient transport mode [148].

The transport of lightweight packages via small drones has demonstrated a 54 percent reduction in harmful greenhouse emissions compared to delivery by a diesel truck in a research study [179]. Similarly, delivery drones are also cleaner and energy efficient when compared to the more prevalent transport mode of electric motorcycles for fast-food meal delivery [142]. Therefore, shifting a portion of the delivery traffic to the third dimension using fleets of autonomous drones could not only reduce traffic congestion in cities, but it could also significantly decrease its contribution to anthropogenic emissions. In addition, substituting for this new delivery paradigm could potentially accelerate the European Union's 2050 vision of de-carbonising the global transport section [95].

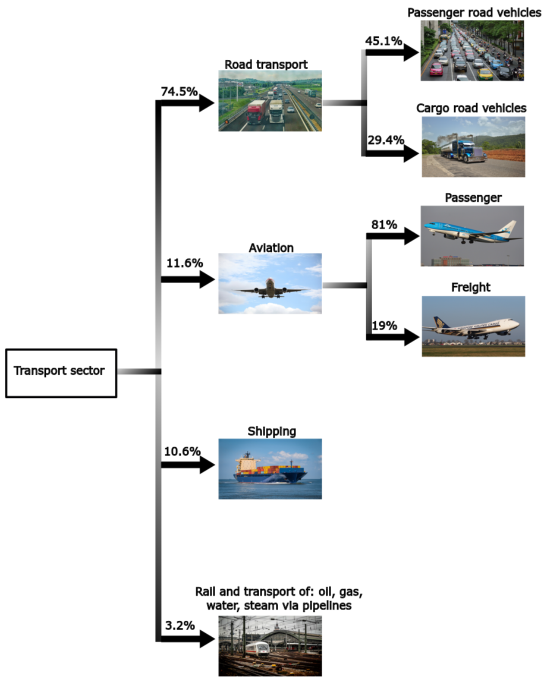

Figure 1.4: Global CO_2 emissions from transport, adopted from [159]. The data represents the global transport emissions in 2018. The images were sourced from Pixabay under the free for commercial and noncommercial use license.

The final factor that is propelling the exploration of drone-based delivery is the last-mile delivery cost, which remains to be the most expensive part of the supply chain. The last-mile delivery segment is estimated to cost more than 53 percent of the total cost of shipping of a single product, which is predominately associated with transport and labour costs[100]. To reduce these cost inefficiencies, the widespread adoption of autonomous drones for last-mile package delivery has been proposed [100].

There remains high potential for drone-based delivery to operate in urban environments. We are not implying that autonomous drone delivery is a panacea to the above societal problems. However, the technology could offer a path towards mitigating those societal problems, if it is optimally deployed. Even though there is compelling case for express drone delivery, it is yet to unfold in cities. The reason for this slow adoption is the plethora of regulatory obstacles across states and cities and most importantly, the lack of infrastructure to safely harbour large volumes of drone in dense and complex environments.

1.2. CHALLENGES AND PREVIOUS RESEARCH

If drone-based delivery follows the trends set by other transport modes, the enormous demand for such novel, efficient and exclusive services could come at the cost of large volumes of drone delivery traffic. The European drone research study by SESAR estimated more than 400,000 drones may accommodate the airspace by 2050 [170]. Another study in the USA projected the number of delivery drones to reach more than 1 million flights per day for the city of Washington DC [134]. These studies all point towards a potential setting where package delivery drones will operate in high traffic densities.

1.2.1. INABILITY TO SAFELY ACCOMMODATE HIGH-DENSITY DRONE TRAFFIC IN URBAN ENVIRONMENTS

It is likely that high-density drone traffic may only be permitted to operate within a thin airspace band known as the Very Low Level (VLL), which spans the altitude of 0-300 m (above ground level) [170]. This means that drones will have to navigate this limited and scarce airspace that is heavily populated with natural and man-made obstacles, such as buildings, high-voltage electrical cables and cell-towers. In addition, this portion of the airspace is also frequently occupied by other airspace users, such as general aviation aircraft and helicopters [147]. As a consequence, accommodating large-scale drone traffic in this complex and constrained urban environment, in a safe and efficient manner, remains the biggest challenge for airspace designers and policymakers.

In terms of flying drones in constrained urban environments, several visions have been offered. A study out of Singapore defined low-altitude drone air routes over existing transport infrastructure that defines flight paths over waterways and urban roads [121, 132]. A similar study also proposed an ensemble of drone routes over a single intersection of an urban street network [98]. Other studies have explored different risk-based path-planning algorithms for drones in constrained environments [141], which include the optimal 3D paths with respect to drone charging stations [14], the transport of packages from a truck to customers [4] and the use of 4D trajectory planning [15]. However, these studies were mainly focused on somewhat very low traffic densities or even single drone operations.

1.2.2. UNCONSTRAINED URBAN AIRSPACE DESIGN

Previous research explored four airspace concepts for the purpose of facilitating extreme traffic densities of futuristic personal air vehicles [182–184]. The study, known as the Metropolis project, revealed one airspace concept, in particular, that scored higher on safety, capacity and efficiency when compared to the rest [184]. The concept was labelled as the 'layers' airspace configuration. The layers concept allocated flights to different altitude bands based on their respective travel directions. Later, a follow-up study investigated the reasons behind the higher performance benefits. The study revealed two factors that were largely responsible for increasing the level of airspace safety, namely, segmentation of traffic and reduction of relative velocities (that is, traffic alignment) between cruising traffic at the same altitude [89]. In a subsequent study, these principles were formalised in a concept called Geovectoring as a tool to design the airspace [88]. Since then, the principles of segmentation and traffic alignment have mainly been explored in traffic capacity studies for the en-route airspace of traditional aviation [181, 182].

However, all these studies have only dealt with free airspace or unconstrained airspace, that is, the airspace above obstacles or free of any obstacles. Therefore, it is still unclear as to how we can apply the principles of the layers concept to a constrained urban environment. There also lies the question of whether it is even logical to add a large amount of structuring constraints to an already confined space and at the same time achieve safe accommodation of high-density drone traffic. To address some of these challenges, we look for inspiration in road-based transportation system where many complexities are shared with road vehicles, especially autonomous cars [79].

1.2.3. ROAD-BASED TRANSPORT DESIGN: ON-GROUND TRAFFIC VS AUTONOMOUS DRONE TRAFFIC

Existing road vehicles provide an informative comparison with drones. This comparison will be much more evident in self-driving vehicles. For example, both emerging transportation modes are projected to navigate in cluttered urban environments and operate in high traffic densities. Of course, there are notable differences. One main difference, for instance, is that drones will operate in a three-dimensional space and the current performance limits of drones imply that it would not be optimal for drones to come to a sudden halt at intersections unlike cars and thus separating opposing traffic flows at intersections will be a difficult task. Although drones in the urban airspace may face circumstances that present somewhat fewer dynamic obstacles than those faced by autonomous cars, safely managing autonomous traffic in a constrained space will be a challenge. However, road design has largely evolved alongside cars to include an array of safety measures to make roads and streets safer for all its users.

Road networks utilise various conflict prevention mechanisms to structure and organise traffic flows [38, 71]. A common structuring enforcement seen on current roads and streets are channelisation planes, which helps demarcate opposite flows of traffic using road markings, islands and raised medians and hence, enabling one-way and two-way streets. Such forms of structuring tends to reduce the risk of conflicts to a certain degree, particularly, at intersections and therefore, are widely used on modern road networks. Given that road vehicles, to a certain extent, are able to safely operate within the current transport networks, means that there is something that we can learn from its infrastructure design philosophies and thus extrapolate to the urban airspace.

1.2.4. RESEARCH OBJECTIVE

This thesis investigates approaches to structure the urban airspace in order to accommodate large-scale drone-based delivery traffic by applying the principles of traffic alignment and segmentation to a constrained urban environment. To perform this research, a research objective is established and followed by a set of comprehensive research questions.

A broad range of studies exists for the topic of unconstrained airspace design for high density traffic. Similarly, a large body of research has focused on navigation, guidance and control of autonomous drones in constrained environments. However, for large-scale drone deliveries to materialise in cities, an effective airspace design is required in order to safely organise such high volumes of traffic in highly constrained environments. Therefore, this leads to the

1

main objective of this thesis:

Main Research Objective

What design paradigms and methodologies from unconstrained airspace research and road transport infrastructure can be translated to a constrained urban airspace for high-density drone traffic operations?

1.3. RESEARCH QUESTIONS

To achieve this research objective, four research questions, together with their sub-research questions, have been defined.

1.3.1. RESEARCH QUESTION 1: DRONE-BASED TRAFFIC DEMAND ESTIMATION

There are several speculations regarding the expected demand of drone-based delivery of small express packages as well as fast-food meals. Due to inconsistencies in the factors used in various drone delivery traffic estimation methods, the traffic estimates have large disparities across geographic regions. Therefore, it is essential to first define what factors play a significant role when estimating traffic density and then establish a coherent framework to estimate the potential traffic demand of drone deliveries of small express packages and fast-food meals for a typical city like New York and Paris. Hence, this raises the first research question:

Research Question 1

What factors should be considered when estimating the potential traffic density culminating from drone-based delivery in a typical urban environment?

1.3.2. RESEARCH QUESTION 2: CONSTRAINED URBAN AIRSPACE DESIGN

The potential of large-scale autonomous drone-based deliveries in cities have broad societal, environmental and economic advantages. However, for these benefits to realise, a number of challenges need to be addressed. As highlighted in section 1.2.1, one main challenge is the safe integration and accommodation of high-density drone traffic in constrained urban environments. To tackle this challenge, we approach the problem from the perspective of two main research domains. First, we aim to learn from prior related work conducted in unconstrained airspace design. More specifically, how we can apply the principles of traffic segmentation and alignment principles to structure and organise high-density traffic flows in a constrained environment setting. Second, we aim to explore the structuring paradigms used in road transport. Most urban streets and road networks feature one-way and two-way lanes, or streets, that safely and efficiently transport large volumes of traffic flow from their respective origins and destinations. With this in mind, the second research question and two supporting sub-research questions were defined:

Research Question 2

How can we use our knowledge from unconstrained airspace design and conventional road transport to design and structure the constrained urban airspace to safely harbour high densities of drone-based delivery traffic?

We approached the above research question by dividing it into two main fundamental elements. As a first step, we explored the different design paradigms employed in unconstrained airspace design by formulating the following sub-question:

Sub-Research Question 1

To what extent can we apply traffic alignment and segmentation principles to a constrained urban airspace environment?

Once the latter sub-research question is solved, we investigate two dominant forms of traffic organisation and structuring methodologies to safely accommodate on-ground traffic flows in urban street networks. In particular, we look at the one-way and two-way street designs, which are largely prevalent in current cities. By gaining inspiration from these design philosophies, we conceptualise and examine two airspace design configurations. To explore the latter and its relevance to a constrained urban airspace environment, the following sub-question is defined:

1

Sub-Research Question 2

What is the performance of one-way and two-way airspace configurations with respect to safety, capacity and efficiency for high-density drone traffic?

1.3.3. RESEARCH QUESTION 3: CATALOGUE THE DIFFERENT PROPERTIES OF CONFLICTS AND INTRUSIONS

Based on the insights from the previous research questions, we set-out to investigate and catalogue the types of conflicts and intrusions observed in the constrained urban airspace configurations. To achieve this, we define the following research question:

Research Question 3

What are the properties of conflicts and intrusions between the urban airspace design configurations?

1.3.4. RESEARCH QUESTION 4: EMERGENT BEHAVIOUR IN CONSTRAINED URBAN AIRSPACE ENVIRONMENTS

To answer the previous research questions, we imposed specific rules and conditions to a single drone. However, we do not know how these drones would behave when they operate in confined spaces in high-density traffic. Therefore, in the pursuit of understanding key emergent behaviour, the following research question was formulated:

Research Question 4

What emergent behaviour and patterns form when we impose rules and conditions to high-density drone traffic in a constrained urban area?

1.4. THESIS OUTLINE

This thesis consists of six chapters, which are chronologically illustrated in Figure 1.5. All chapters, apart from Chapter 1 (Introduction), Chapter 4 and Chapter 6 (Discussion), originate from peer-reviewed journal publications, for which its

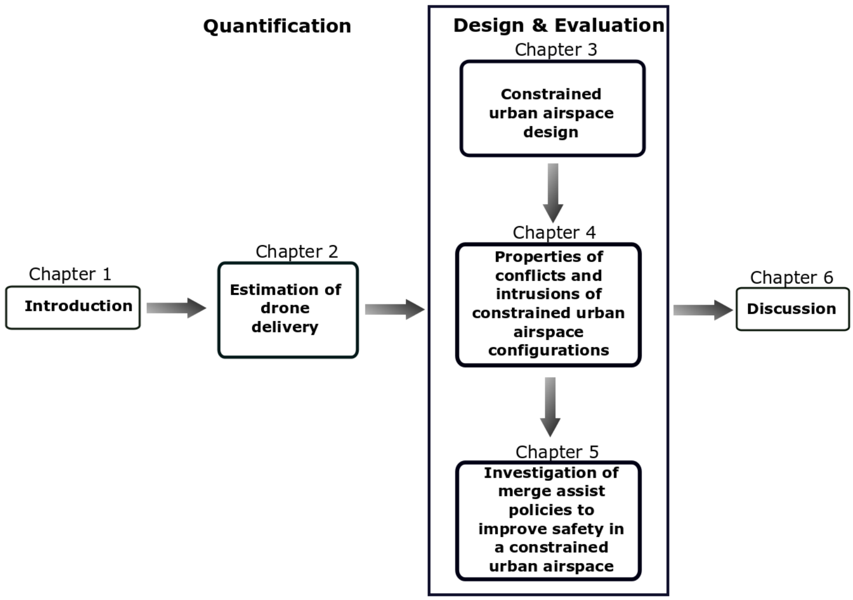

Figure 1.5: Structure of the thesis. The rectangles correspond to their associated chapters that are assembled in chronologically order. Chapter 2 features the quantification aspect of the thesis while chapters 3 to 5 cover the design and evaluation part of the thesis. The material presented in chapters 2 to 5 originate from peer-reviewed publications.

content corresponds to the content in each chapter. In each chapter, an introduction is given that explains its position to the overall research. Further, every chapter provides a publication summary, which gives the original title of the study, its respective co-authors and where the research was published.

Chapter 2: Estimation of traffic density of drone-based delivery in urban areas
This chapter presents a framework to determine the traffic density of express package delivery drones for a typical city. The chapter also discusses the potential of fast-food meal delivery via a fleet of autonomous drones for one example of a quick service restaurant. To further emphasise on the benefits of drone-based delivery, a comparison is presented between traditional delivery modes. Important challenges that are yet to be addressed by policymakers and researchers of unmanned traffic management programs, such as U-Space in Europe, are also discussed. Here, a key challenge is identified that may unlock large-scale drone-based delivery missions in dense urban areas.

Chapter 3: Constrained urban airspace design

This chapter presents the design of two novel airspace concepts of a constrained urban environment for the purpose of accommodating high volumes of drone delivery traffic. The two concepts bear resemblance to that of road-based design and thus having two-way and one-way streets by imposing horizontal structure. The chapter applies the concepts to the airspace of Manhattan, New York, which is heavily constrained by a multitude of physical land-form structures and existing street networks. Both airspace concepts utilise heading-altitude rules to vertically segment traffic with respect to their travel direction. In addition, both concepts feature transition altitudes in order to facilitate turning flights that require to decelerate to make safe turns at intersections. The chapter compares and evaluates the performance of the concepts using fast-time simulations experiments.

Chapter 4: Properties of conflicts and intrusions of constrained urban airspace configurations.
The content in this chapter is an extension of research presented in chapter 3. In the pursuit of demonstrating the intricate differences between the two-way and one-way airspace configurations, this chapter explores and analyses the salient conflict and intrusion properties. By using fast-time simulation experiments, the statistics of in-trail, crossing and head-on conflicts and intrusions are captured and analysed for multiple traffic demand levels. Further, the chapter presents the identification of geographical hotspot regions at which conflicts occur by using conflict maps.

Chapter 5: Investigation of merge assist policies to improve safety in a constrained urban airspace
The previous chapter demonstrated that a large proportion of conflicts and intrusions are triggered when flights merge to their respective altitude layers. These transitions to different altitudes mainly take place before and after intersections since flights require to change headings and thus climb or descend to different altitudes, respectively. Because of this, a majority of merging conflicts were identified to be primarily situated near intersections. To circumvent the probability of merging conflicts occurring at intersections, this chapter investigated two merging-assist frameworks that are widely used in road traffic. The chapter therefore presents two policies to reduce the likelihood of merging conflicts. The performance of the method was evaluated using fast-time simulation experiments with respect to safety. In addition, the chapter presents a mesoscopic analysis of the urban street network, which aims to increase our understanding on the performance of the merging-assist frameworks used in our experiments.

Chapter 6: Discussion and conclusions.
This chapter revisits the research questions and it presents a discussion of the main findings of this thesis. The chapter provides recommendations for future research based on the work performed in each individual study of this thesis. Further, it illustrates how the research can be extrapolated and applied by policymakers of advanced air mobility program and the associated unmanned traffic management programs. Finally, the chapter ends with a discussion on how the societal impact of autonomous drone delivery could potentially be accelerated by evoking the right policy decisions, fostering public acceptance and trust and encouraging technical development.

2

ESTIMATION OF DRONE-BASED DELIVERY TRAFFIC IN URBAN AREAS

This chapter presents a framework to estimate the traffic density of small express package delivery drones for a typical city. The chapter compares the feasibility of fast-food meal deliveries using a fleet of autonomous delivery drones versus delivery via e-bikes. A discussion on a set of challenges that are yet to be tackled by unmanned traffic management programs is presented. Here, a key challenge is identified that may unlock the use of large-scale drone delivery missions in dense urban areas.

The content of this chapter has been published in:

M. Doole, J. Ellerbroek, and J. Hoekstra. Estimation of traffic density from drone-based delivery in very low level urban airspace. *Journal of Air Transport Management*, 88, 101862, 2020.

2

2.1. Introduction

Rapid technological advancement of unmanned aerial vehicles, commonly referred to as drones, together with growing consumer demand, have sparked interest in the use of such vehicles in a variety of applications. For example, companies such as Amazon [148], Jingdong [161] and UPS [81] are investigating drone-based delivery of small packages for the last-mile segment (i.e. the segment between the distribution centre and final destination) in urban environments. Also fast-food restaurants such as McDonald's [187] and Domino's [145], are investigating drones to deliver fast-food meals in dense urban settings.

One of the reasons for this growing interest is the saturation of ground transportation means in dense cities. The population growth of major cities is increasing at a rapid pace [152] which places enormous stresses on the transportation network in order to meet the demands of urban inhabitants [3]. This results in transportation gridlocks that have economic (Economist, 2018) and environmental implications [179].

Last-mile delivery is considered to be a choke point for the delivery of packages to consumers, especially for e-commerce companies [61]. This final segment of the supply-chain accumulates the largest costs, stemming primarily from transport and labour costs [100]. It is estimated that the last-mile delivery expends the global parcel delivery industry almost $85 billion per year [100]. This corroborates the reason why Amazon and UPS are investigating drone deliveries in urban areas as a viable solution. However when this materialises, the Very Low Level (VLL) urban airspace (i.e. the portion of the airspace assigned for drones by regulatory bodies) will experience high densities of drone traffic flying in close proximity to natural and man-made obstacles. To explore these commercial demands, Unmanned Traffic Management (UTM) programs such as U-Space in Europe, are developing critical services such as deconfliction management and dynamic capacity management [171].

An outlook study by SESAR estimated 70,000 delivery drones for Europe by 2035 (SESAR, 2016). Other studies discuss possible drone-based delivery traffic densities, focusing on small cities in the US [134]. Research has also been done for determining the optimal placement of distribution centres for drone deliveries in European cities [11].

However, there is no established method for estimating the traffic densities resulting from drone-based delivery for typical European cities. As a result, operational solutions that deal with where, how and when to fly high densities of delivery drones in VLL urban airspace, may have limitations concerning safety and capacity.

The goals of this paper are threefold. In this paper we aim to develop an understanding for estimating the traffic density of parcel delivery drones for a typical dense European city. In addition, we aim to provide a reality check to the feasibility of one application: fast-food meal order delivery via a fleet of drones for a European city. Lastly, we highlight the resulting challenges for U-Space in unlocking the potential for high-density drone traffic in VLL urban airspace.

A selection of the work presented in this paper is an extension of the research originally reported in [50] by the same authors. The current paper contributes to this study by updating the statistics of drone-based parcel volumes, improving the overall analysis of the study and, by providing a reflection of key challenges that need to be addressed in future U-Space research studies.

The research in this chapter is organised in sections. Section 2.2 outlines the fundamental assumptions employed for the parcel demand and traffic density calculations. Section 2.3 lays out an overview of the estimation framework utilised in this study. It then uses this framework to estimate the drone-based parcel delivery demand for five European countries: Germany, UK, France, The Netherlands and Belgium. The section presents a forecast of the drone-based parcel delivery demand for the years between 2035 and 2050 for each country. In addition, the section discusses a case-study of drone-based traffic density numbers for Paris metropolitan area. Section 2.4 presents a reality check on fast-food delivery via a fleet of drones and it establishes the traffic density for this transport mode. Section 2.5 presents important challenges that need to be addressed by U-Space in order for drone-based delivery to materialise. Finally, Section 2.6 recaps the key ideas of the paper and presents avenues for future research.

2.2. ASSUMPTIONS

The performed analysis to identify the potential demand of drone-based delivery of packages and its resulting traffic density in this study is based on the following set of assumptions:

1. In order to avoid cross-border complications, only domestic (national) parcels are considered. According to global courier company UPS, 85 percent of parcels are delivered domestically, and the remaining 15 percent are internationally-bound parcels [197]. Hence, this assumption can be incorporated into this study in order to exclude parcels with international destinations.

2. Only deliveries within an urban area are eligible for drone-based delivery. This is because the focus of the current paper is on understanding the drone-based delivery traffic in an urban airspace.

3. Only a proportion of parcels are suitable for drone delivery since not all parcel deliveries are economically viable to be transported by drones. A previous drone-based parcel delivery estimation study assumed only 70 percent of urban parcel deliveries eligible for drone delivery [134]. According to the latter study, the remaining 30 percent represent deliveries where the volume of delivery to a particular area is so high that it becomes more economical to employ traditional transport modes such as trucks or vans.

4. Parcels weighing less than or equal to 2.2kg are delivered by drones. This is needed to keep the operating cost low [44]. More importantly, 86 percent of E-commerce orders from Amazon adhere to this weight constraint.

5. Only the last-mile segment of the delivery is considered in this study since it is the most promising segment for delivery drones ([44, 59, 60, 100, 179]).

6. In this study a drone-based delivery takes an average of 30-minutes in total to deliver a single package per trip (i.e., 30-minutes to for a single drone to fly to the destination, to deliver the package and for it to return to base). However, it is plausible that this assumption of one parcel delivery by a single drone will change in the future with improved drone technology, which would allow delivery of multiple parcels per delivery trip.

7. The number of operational days for drone delivery is highly dependent on meteorological conditions such as wind speed and precipitation. The drone model employed in this study is capable of operating up to a maximum wind speed of 8m/s and cannot fly during precipitation ([49]). According to ([129]) a typical European urban city such as Paris experiences, on average, winds exceeding 8m/s as well as some precipitation for approximately 20 percent of the days per year. In this study, we take a conservative assumption of 20 percent to represent no-fly days per year. While the remaining 80 percent represents guaranteed can-fly days. However, with technology development, we expect the proportion of no-fly days owning to weather effects to become minimal in the future.

2.3. DEMAND PREDICTION FOR PARCEL DELIVERY DRONES

This section demonstrates the approach to estimate the traffic density of parcel delivery drones. The methodology followed in this study is illustrated in Figure 2.1. For this analysis, the parcel numbers for five European countries, that we deemed interesting, were employed. The parcel numbers for the five states include: Germany, the United Kingdom (UK), France, the Netherlands (NL) and

Belgium. After extracting the number of parcels for the latter countries, the relevant assumptions described in Section 2.2 were applied for each state in order to estimate the viable number of parcels for urban areas. Subsequently, growth factors were used to depict the demand for parcel delivery drones for three variant scenarios. Thereafter, the estimates for France were narrowed to identify the traffic density of parcel delivery drones for Paris metropolitan area. Note that the motivation for selecting Paris was to make the results of this study comparable to past research (such as [5]).

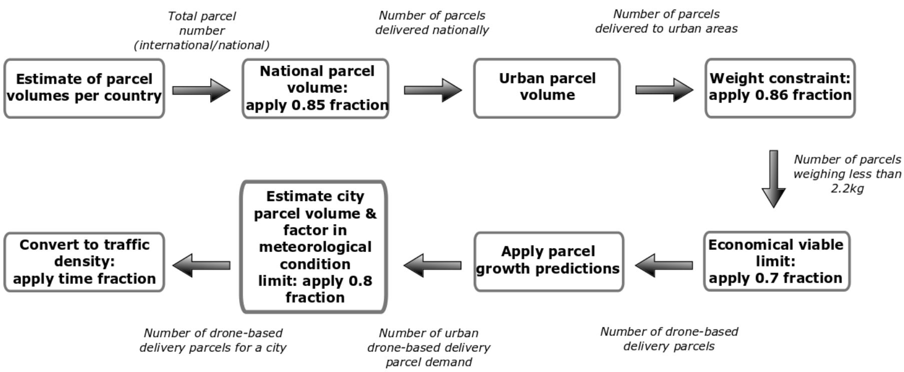

Figure 2.1: Framework diagram to estimate the traffic density of drone-based delivery parcels in an urban airspace.

2.3.1. EXISTING DELIVERY PARCEL VOLUMES

In 2017, 74.4 billion parcels were delivered worldwide. According to a report published by Pitney Bowes, this number was primarily driven by the strong growth of e-commerce giants such as Amazon and Alibaba ([149]). The 2017 figure was an increase of 17 percent compared to 2016 ([37, 150]) and it is expected to surpass 100 billion in 2020 ([150]).

According to ([149]), Germany, UK, and France recorded parcel delivery volumes of 3.4, 3.2 and 1.2 billion in 2017 (See Table 2.1), which accounted for an average increase of 6 percent relative to 2016. Similarly, the Netherlands had 350 million delivery parcels in 2016 which was an increase of 12 percent compared to the 2015 numbers ([2]). Assuming a slightly higher growth of 15 percent for the year 2017, equates to 402.5 million delivery parcels for the Netherlands. Lastly, the Belgium Post (the national postal agency for Belgium) reported to have handled 190,000 parcels on a daily basis in 2017 ([31]). This amounts to approximately 69.4 million delivery parcels in Belgium for 2017.

Table 2.1: Recorded number of parcel delivery volume for five European countries in 2017.

	Germany	UK	France	NL	Belgium
Number of delivery parcels	3.4 billion	3.2 billion	1.2 billion	402.5 million	69.4 million

Table 2.2: Expected number of delivery parcels for five European countries in 2019.

	Germany	UK	France	NL	Belgium
Number of delivery parcels	4.0 billion	3.7 billion	1.4 billion	469.8 million	81 million

In order to estimate the above parcel delivery numbers for 2019, for the respective countries, it is assumed that all five countries experienced an average growth rate of 8 percent (from 2017 to 2019) yearly ([150]). This forecast is presented in Table 2.2. The estimates in Table 2.2 include both national and international delivery parcels. Since this study investigates the demand for drone delivery per country, internationally-bound delivery parcels are excluded and focus was given to domestic parcels which are eligible for drone delivery. According to global courier company UPS, 85 percent of delivery parcels comprise of domestic bound parcels in the US ([197]). Assuming the same holds true for the five European countries in this study, results in domestic parcel delivery numbers (see Table 2.3).

Table 2.3: Expected number of domestic/national delivery parcels for five European countries in 2019.

	Germany	UK	France	NL	Belgium
Number of delivery parcels	3.4 billion	3.14 billion	1.19 billion	399.3 million	68.8 million

2.3.2. NUMBER OF PARCELS DELIVERED TO URBAN AREAS

In 2018 the World Bank ([206]) estimated that approximately 77 percent of the Germany's population reside in urban areas. Similarly, in the UK, 83 percent of the population are concentrated in urban environments. France has 80 percent of its inhabitants in urban cities while the Netherlands and Belgium holds 91 and 98 percent of their population in urban areas, respectively. These percentages have remained constant since 2016 and therefore, it can be assumed that the fraction of the population living in urban areas remains the same through

2019 ([206]). By factoring the urban population percentages to the number of national delivery parcels given in Table 2.3, equates to the number of parcels delivered to urban areas for each of the five countries (Table 2.4). Note that this is a conservative estimate, as the per-capita demand in urban areas is often larger than, not equal to the demand for e-commerce in rural areas ([80]).

Table 2.4: Expected number of delivery parcels to urban areas for the five European countries in 2019.

	Germany	UK	France	NL	Belgium
Number of delivery parcels	2.61 billion	2.6 billion	952 million	363.4 million	67.4 million

2.3.3. NUMBER OF URBAN DELIVERY PARCELS LESS THAN OR EQUAL TO 2.2KG

The above parcel numbers comprise of parcels with weights up to 31.5kg ([149]). Several drone delivery companies such as Amazon Prime Air, Matternet and Flirty have focused design efforts on transporting 2.2kg over a distance of 10km, which according to ([44]) is the optimal design requirement with respect to operating costs. According to Amazon, 86 percent of parcels delivered are below 2.2kg ([148]). Since the demand for delivery parcels are primarily driven by the growth in e-commerce, it is a reasonable design requirement for the urban airspace to accommodate such realistic traffic densities. Taking into account the 86 percent factor, results in the number of delivery parcels eligible for drone transport for the five European states (Table 2.5). Note that economic and technical developments could increase the maximum weight at which packages are (economically and technically) feasible to be transported by drone. In this case the 86 percent fraction used in this paper is a conservative estimate.

Table 2.5: Expected number of delivery parcels to urban areas that satisfy the weight limit of 2.2kg for the five European countries in 2019.

	Germany	UK	France	NL	Belgium
Number of delivery parcels	2.24 billion	2.23 billion	818.7 million	312.5 million	58 million

2.3.4. NUMBER OF PARCELS ELIGIBLE FOR DRONE DELIVERY

The economic advantages for employing drones in-place of traditional transport modes (trucks and vans) for last-mile delivery have been demonstrated in several studies ([44, 59, 60, 100, 179]). The last-mile is defined as the segment between the distribution centre and the final destination. It is assumed that only for 70 percent of the urban packages, drone delivery will be economically viable ([134]). The remaining 30 percent are package deliveries in areas where the volume of delivery is so high that it becomes more economical to employ traditional transport modes such as trucks or vans. The values in Table 2.5 should therefore be multiplied by a factor of 0.7, resulting in a set of estimates for drone-enabled delivery parcels in urban areas for the five countries for 2019, shown in Table 2.6.

Table 2.6: Expected number of drone-enabled delivery parcels in urban areas for 2019.

	Germany	UK	France	NL	Belgium
Number of delivery parcels	1.57 billion	1.56 billion	573 million	218.7 million	40.6 million

2.3.5. FUTURE GROWTH IN THE NUMBER OF DELIVERY PARCELS BY DRONES

The SESAR U-Space outlook study postulates delivery drone services to be viable by 2035 ([170]). In order to be synchronised with the SESAR U-Space program, we perform a forecast to estimate the number of drone-eligible parcel deliveries for the five European countries until 2050. To be conservative with the drone-based parcel delivery demand forecast, the average economic growth rate is used, which stands at 1.8 percent for Europe as of 2019 ([36]). If we assume the demand for drone-based delivery to be aligned to the average economic growth rate for the next 30 years for the five countries, three different scenarios (low, medium and high) can be explored in this study. In a low growth scenario, we assume the economic growth to be half of 1.8 percent (i.e., 0.9 percent) per year for the next 30 years. While for the medium growth scenario, we assume that the current 1.8 percent to represent the average growth until 2050. Under the high growth scenario, we consider the yearly growth rate to be twice of 1.8 percent (i.e., 3.6 percent per year). The extrapolated results in annual drone parcel delivery numbers for each of the five countries, from the baseline year 2019 to 2050, is presented in Figure 2.2.

2.3.6. ESTIMATE FOR THE TRAFFIC DENSITY OF PARCEL DELIVERY DRONES IN PARIS

The Paris metropolitan encompasses approximately 12.5 million people within an area of 12,012 km^2 ([97]). Taking into account a 0.5 percent growth since 2015 ([97]), amounts to 13.1 million inhabitants in the Paris urban area for 2019. This

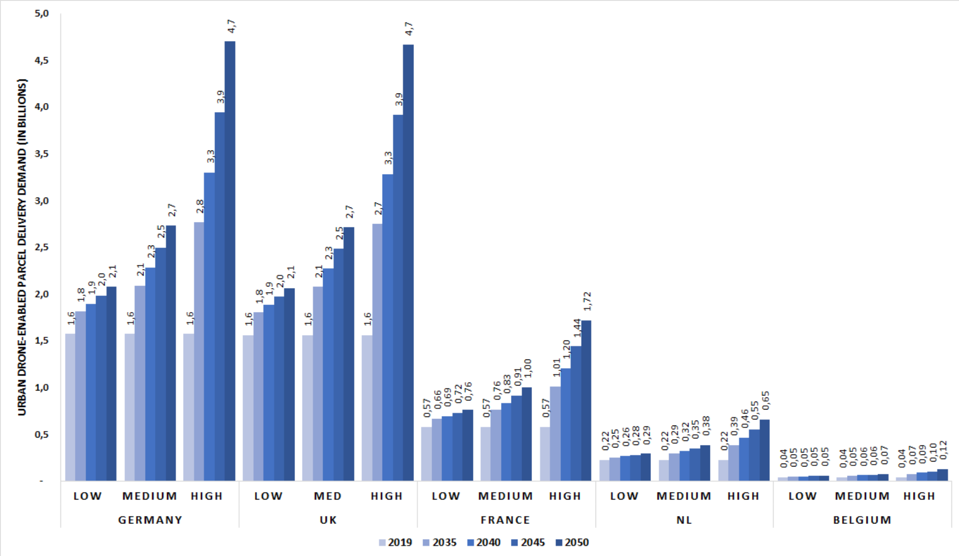

Figure 2.2: Urban drone-enabled parcel delivery demand for three variant scenarios of 0.9, 1.8 and 3.6 percent average yearly growth rates until 2050. The year 2019 is the baseline year for the extrapolation.

figure represents 24 percent of the total urban population (54 million) of France ([207]). This 24 percent was incorporated into the values represented for France in Figure 2.2 in order to obtain estimates for the annual number of drone-eligible delivery parcels in Paris, as presented in Table 2.7.

Table 2.7: Expected number of eligible parcels for drone delivery in the Paris metropolitan area per year for 2035-2050.

Year	Low	Medium	High
2035	158.4 million	182.4 million	242.4 million
2040	165.6 million	199.2 million	288 million
2045	172.8 million	218.4 million	345.6 million
2050	182.4 million	240 million	412.8 million

With the assumption that drone deliveries only take place 80 percent of the days per year due to favourable meteorological conditions (see assumption 7 of Section 2.2), within an eight-hour operating time-window (based on the average hourly work-day schedule), the hourly demand for parcel deliveries by drones is computed for Paris (Table 2.8). The drone delivery traffic movements for the realistic scenario (which postulates a 1.8 percent growth in parcel delivery demand), expects a traffic volume of 78,082 flights per hour within the urban airspace of Paris in 2035. According to Amazon, a single delivery drone is able to deliver a parcel over a maximum distance of 10km within an average flight time of 15 minutes ([148]). In keeping with Amazon's delivery time estimation, it is assumed that a single drone has a total round-trip time (time to deliver and return to home-base) of 30 minutes, which includes the time to fly to the respective destination, make the delivery to the customer and to return to home-base. As a result, the traffic density of delivery drones is obtained by dividing the traffic movements per hour by a factor of two for the urban area of Paris (Table 2.9). The traffic numbers represented in Table 2.9 reflect the potential drone-based parcel delivery urban airspace traffic densities that may arise in the future, provided that safety concerns and societal acceptance have been addressed.

Table 2.8: Expected number of parcel delivery drone movements (drone flight traffic volume per hour) in the Paris metropolitan area for three variant scenarios.

Year	Low	Medium	High
2035	67,808	78,082	103,767
2040	70,890	85,274	123,288
2045	73,973	93,493	147,945
2050	78,082	102,740	176,712

Table 2.9: Expected traffic density of parcel delivery drones in the Paris metropolitan area for three variant scenarios.

Year	Low	Medium	High
2035	33,904	39,041	51,884
2040	35,445	42,637	61,644
2045	36,987	46,747	73,923
2050	39,041	51,370	88,356

Traffic density is an important metric in airspace design. It can be employed to investigate the safety and capacity of different airspace design concepts. The expected traffic density volumes of aerial vehicles are already significantly higher when compared to the current global commercial aircraft traffic, which record approximately 10,000 flights per hour on average, globally ([65]). In addition, there have been recent experiments in using drones to deliver fast-food in dense urban environments by companies such as Google Wing, UberEats and Flytrex ([24, 124, 128]). These companies are interested in drone delivery to be able to meet shorter delivery times at lower costs. This means that the demand for drone-based delivery may further increase. When considering that the probability for traffic conflicts grows quadratically with traffic density ([84]), managing airspace complexity will be one of the main challenges of unmanned traffic management concepts such as U-Space.

2.4. Fast-food meal delivery cost comparison between drones and E-bike modes

The online food-delivery industry is growing rapidly, mainly due to higher customer satisfaction levels which is propelled by shorter delivery times ([83]). To cope with this demand, restaurants use third-party logistic providers, or employ couriers, to perform deliveries via electric-bicycles (E-bikes). Despite such food-delivery options being ubiquitous in cities, there are disadvantages. For example, delivery via E-bikes present a safety hazard to pedestrians and other road-users in cities ([166, 185]) and the cost of labour erodes profit margins ([104]). E-bikes may also become affected by traffic congestion thus creating delays to delivery schedules ([185]). Because of this, several companies have performed field tests on novel transport modes such as drones for food-delivery tasks. Recent studies have investigated different food-delivery dispatch algorithms for drones ([119]) and also, studies have been done in understanding customer behaviour towards drone food-delivery ([93]). However, little is known about the economic feasibility and the resulting traffic densities for drone delivery of fast-food meals in dense urban areas.

This section explores the costs associated to operating drone food-delivery for a cluster of fast-food restaurants in Paris metropolitan area. The costs are compared to the existing logistics mode of E-bikes. An estimate is obtained for the traffic density arising from drone food-delivery in order to determine the overall delivery drone numbers for Paris. Therefore for this case-study, a comparison is made between the DJI Matrice 600 Pro (a hexa-copter drone modified for food-delivery) and traditional E-bikes (battery-assisted bicycles) in food-delivery (Figure 2.3).

Figure 2.3: Example of a fast-food delivery quad-copter drone, adapted from ([111]); and a typical fast-food delivery E-bike with an integrated delivery cargo box, adapted from ([191]).

2.4.1. ESTIMATING THE NUMBER OF DRONES AND E-BIKES

According to ([188]), the quick-service restaurant chain McDonald's, in France, served 1.8 million meals per day across its 1,464 restaurant stores in 2019. A study in 2012 by ([138]) estimated that approximately 57 percent of meals sold at hamburger restaurants, such as McDonald's, represented take-out/delivery meals. Given a 3.5 percent growth in food-delivery meals per year from 2012 to 2019 ([83]) results in 72.5 percent of the proportion of meals being delivery meals. Of note, this fraction of delivery meals is also aligned with the recent trends in online food delivery, suggesting that delivery meals are increasingly more popular than dine-in meal orders ([133]). As a result, the number of delivery meal orders per day amounts to 1.3 million across the 1,464 restaurants. In our model we use McDonald's as a potential case-study restaurant due to the general availability of data and its interest to employ drones for food delivery in the future ([187]). Given these statistics, we can estimate the number of meal deliveries per hour per restaurant kitchen. Assuming a uniform distribution of meals per day in all restaurants, this equates to approximately 888 meals per day per restaurant kitchen. According to ([196]), typical restaurants serve the greatest demand within a seven-hour time-window per day (i.e., between lunch time from 11:00 to 14:00 and between dinner time from 17:00 to 21:00). Furthermore, we assume that the latter demand is evenly spread across the seven-hour period. As a result, the number of meal orders per hour per kitchen amounts to approximately 127. Due a lack of data, for the analysis, the number of McDonald's restaurants situated in Paris metropolitan area was obtained from OpenStreetMap data. The data generated from OpenStreetMap resulted in 291 restaurants belonging to the McDonald's fast-food chain within the specified area (see supplementary information appendix 1). From the estimated 888 meals per day per restaurant kitchen, the total number of potential meal delivery orders for Paris metropolitan sums to 258,408, which results to roughly 36,915 meal orders per hour.

Similar to the assumptions employed in section 2.3, we assume a drone takes 30 minutes on average to deliver a single order to one customer (see assumption 6 of Section 2.2) and return back to one of the 291 restaurant kitchens. This results in 18,458 food-delivery drones as presented in Equation 2.1. To match the previously-mentioned hourly delivery demand rate for the 291 kitchens, it is assumed that the total number of delivery drones are uniformly distributed among the 291 kitchens.

$$\text{Number of delivery drones} = \frac{36{,}915 \text{ meal orders}}{1 \text{ hr}} \times \frac{1 \text{ drone}}{2 \text{ meal orders/hr}} = 18{,}458 \text{ delivery drones} \tag{2.1}$$

$$\text{Number of delivery E-bikes} = \frac{36{,}915 \text{ meal orders}}{1 \text{ hr}} \times \frac{1 \text{ drone}}{5 \text{ meal orders/hr}} = 7{,}383 \text{ delivery E-bikes} \tag{2.2}$$

In the case of E-bikes, the capacity of a cargo box is used to estimate the number of meals that can be delivered per hour per trip. According to ([56]), a food-carrying cargo box has an estimated capacity to carry five large pizzas/large meals. Therefore, in this study it is assumed that an E-bike can transport five meals per hour to five independent customers. Taking into account the hourly meal order rate, 36,915 orders per hour, this results in 7,383 E-bikes (illustrated in Equation 2.2) to meet the demand. Furthermore, the total hourly meal order demand is uniformly distributed across the 291 kitchens. This means that all 291 restaurants will require 7,383 E-bike couriers to operate and handle the delivery of hourly meal orders.

In order to estimate the cost of delivering fast-food via the two transport modes, three variant scenarios are employed. The scenarios include: conservative, high potential and high acceptance. Note that the scenarios names used are based on the SESAR Outlook study ([170]). Scenario 1, which assumes a conservative scenario case foresees a future of harmonised legislation hence permitting Beyond-Visual-Line-Of-Sight (BVLOS) flights post 2020 and social concerns that limit urban delivery in specific regions of cities. Scenario 2, high potential, predicts a future where multiple large-scale delivery service providers integrate drone delivery to their delivery fleet and drone-based delivery gradually begins to accelerate demand. Scenario 3, which assumes higher acceptance scenario case, forecast a scenario where there is a rapid growth in technology, such as fully autonomous flights thus improving safety and, decrease of costs due to economies of scale. Each of these scenarios will be compared against cost variables for each transport mode. Ultimately, the costs will be compared to the traditional electric-bicycle delivery mode.

2.4.2. DELIVERY DRONE COST VARIABLES

This section presents the cost variables that are employed to estimate the cost of delivering a fast-food meal order using a fleet of drones.

COST OF DRONE

The cost of the drone (i.e., DJI Matrice 600 Pro) for the conservative scenario was obtained from a manufacturer's cost estimate ([48]). This cost estimate is priced at €5,699 per unit and it is far higher than its competitors. This price-point can be considered to be a conservative case and hence why it is used in the conservative scenario. For the high potential case, the cost of a drone is assumed to be 75 percent of the conservative scenario cost while in the high acceptability scenario the cost of the aerial vehicle is assumed to be 50 percent of this cost estimate. This reduction in the cost of a drone can be reasoned by the future decrease in the sensor technology costs. The cost decrease of drones could mimic the sharp decrease of prices for mid-range smartphones ([25]).

COST OF MODIFICATION

Modification is required to equip the drone with a payload-carrying capability i.e., a lightweight payload hull to house the fast-food meal order. In the conservative scenario, it is assumed that the modification cost is borne by the client. Realistically, the manufacturer could charge a reasonable price for modifications. As the demand increases, we assume that the economies of scale will help reduce the cost of modification to zero. This can be seen in the high acceptability scenario.

COST OF BATTERY

The drone battery is recharged at the respective restaurant at which the drone is stationed at. In order to ensure uninterrupted service, the drained battery, from the respective drone, is unloaded for it to be recharged at a charging station. Subsequently, a fully-charged battery is loaded onto the drone. As a result, each drone will require an additional battery, hence incurring a cost. The price of lithium-ion batteries is likely continue to decrease yearly ([26, 39]). A recent analysis estimated the average selling price of lithium-ion battery packs to be €175/kWh which is a 24 percent decrease since 2016 and 79 percent decrease since 2010 ([39]). By 2025 the price of a lithium-ion battery pack is projected to decrease to €84/kWh ([26, 39]). The manufacturer's ([48]) cost estimate for an extra drone battery is priced higher compared to its competitors. Therefore, the cost of an extra battery, seen in the conservative scenario, is taken from the manufacturer's cost estimate. And, in a high potential scenario, the cost of the manufacturer's drone battery is estimated to decrease by 50 percent to match the competitor price-point. Similarly, in the high acceptability scenario, we assume the cost of the battery to decrease by 75 percent in the future, as predicted by ([195]).

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Annual maintenance cost per drone

The need for maintenance will decrease with the evolution of drone technology. Currently, the maintenance cost is assumed to be 30 percent of the cost of the vehicle for the conservative scenario. This is a relatively high cost for maintenance and as the cost of the vehicle decreases together with further advancement in technology, the cost of maintenance will decrease. The high potential scenario is expected to reduce the annual cost of maintenance to 10 percent of the cost of the vehicle and 5 percent of the cost of the drone for the high acceptability scenario.

Annual liability insurance cost per drone

The liability insurance cost for delivery drones is still not well defined due to its novelty. According to ([115]), the cost for the annual liability insurance for consumer drones ranges between €600 to €1,600 per drone. We believe that as drones become increasingly intelligent, and as U-Space unfolds to become a matured ecosystem for drones, the cost of annual insurance will decrease. According to ([194]), the cost of insurance for drones is predicted to decrease due to competitive pricing as more insurance providers enter the market. Therefore, based on the above reasons we can estimate the cost for the yearly liability insurance for a delivery drone. Hence, we assume for a conservative case, the cost of insurance to be €1,000 while for the high potential case the price should be €500 and, more optimistically, €100 per year for the high acceptability scenario.

Number of drone operators

The number of operators for operating/piloting (i.e. flight planning, monitoring and tracking, servicing etc.) of delivery drones is assumed to be dependent on the level of autonomy. Loading food parcels (unloading is assumed to be done by the recipient/customer at the final delivery location) and handling the delivery drone, i.e., packaging and loading of food, is assumed to be performed by existing restaurant employees thus warranting for no specialised personnel to handle and load food parcels. This is likely to be similar to how existing quick-service restaurants employees operate online food-delivery applications, supplied by Uber Eats or Deliveroo, with minimum training and no additional salary increment. The conservative and high potential scenario is assumed to require more than one operator. In particular, the number of drone operators for the conservative scenario is five operators per kitchen, hence resulting in 1,455 operators in total. For the high potential scenario, it is assumed that progress in drone technology will increase its ease of use and the level of autonomy, thus reducing the number to two operators per kitchen, which equates to 582 operators in total. Similarly, the high acceptability scenario assumes to have full autonomy hence, this scenario will not require many operators. As a result, only a single operator is assumed to be stationed for each kitchen, which amounts to 291 operators.

LABOUR COST PER HOUR

This cost is attributed to employing drone operators. The labour cost is assumed to reduce with increasing level of autonomy. According to ([144]), the average cost of labour per hour for a drone operator in the US can vary roughly between €15 and €50. Assuming an equal pay-scale in France, we use €30 (rounded average of the latter lower and upper hourly labour costs) as the hourly cost of labour for the conservative scenario as a consequence of high demand and skill of labour needed to manually, or semi-automatically, operate a drone in a complex urban environment. Similarly, as the operational use of delivery drones reduce in complexity with the supply of full autonomy, which might only require entering of the recipients address, the cost of labour will decrease. For this reason, the cost of labour for the high potential and high acceptability scenario is assumed to decrease to €20 per hour.

AIRSPACE COST PER DRONE PER HOUR

The cost of utilising the airspace can be viewed as a measure to control congestion in addition to making UTM/U-Space a profitable business. Hence there will always be a cost for using the airspace. However, UTM and U-Space have yet to establish such unit economics. As a result, the airspace utilisation cost will need to be assumed for this analysis. For the conservative scenario, a cost of €2 per hour per drone is assumed. For the high potential and high acceptability cases, the cost for airspace is assumed to decrease and represent €0.50 and €0.25. This is assumed to take place as U-Space unfolds progressively with time.

NUMBER OF OPERATIONAL DAYS

Due to meteorological conditions such as high winds and precipitation, not all drone flights will be guaranteed all-year round. A proportion of the drone-based delivery flights will experience no-fly days. Based on such data, we take a conservative assumption of 20 percent to represent no-fly days per year for our study (see assumption 7 of Section 2.2). This assumption is applied across all three scenarios in Table 2.10. However, note that as technology advances we expect a decrease in the proportion of no-fly days per year, especially during mild precipitation periods.

2.4.3. DELIVERY E-BIKE COST VARIABLES

This section presents the cost variables that are used to compute the delivery cost of a meal order via E-bikes.

COST OF E-BIKE

This cost is given by the manufacturer's catalogue in ([55]). The manufacturer's cost estimate is used for the high potential scenario. Depending on the external factors such as tax initiatives, the cost of an E-bike in a conservative scenario is assumed to be €2,500 per bike. Similarly, in high potential and high acceptability scenarios, the cost of the E-bike is assumed to decrease by 25 and 40 percent respectively lower due to factors such as tax incentives, economies of scale and competitive pricing.

COST OF MODIFICATION

This involves costs associated to integrating the E-bike with a special food transport box in order to keep the meals warm. An average size box cost approximately €150 according to ([55]). This is assumed to be the cost for the conservative case. For the high potential case and high acceptability case, the costs is assumed to be €100 and €50.

COST OF BATTERY

To enable uninterrupted food-delivery, each E-bike is assumed to have an extra battery. In the event of a drained battery, it can be unloaded and a fully-charged battery can be loaded at the respective restaurant at which the E-bike is stationed at. Similar to the delivery drone, the cost of lithium-ion batteries is assumed to decrease by 50 and 75 percent respective to the conservative price scenario which was derived from the manufacturer's catalogue ([55]).

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Table 2.10: Drone-based food-delivery costs estimation for pessimistic, realistic and optimistic scenarios.

	Delivery drone		
Parameter	Conservative	High potential	High acceptability
Number of drones	18,458	18,458	18,458
Cost of drone (€)	5,699	4,274	2,850
Cost of modification per drone (€)	150	100	0
Cost of extra battery (€)	899	450	225
Annual maintenance cost per drone (€)	1,710	427	142
Annual liability insurance cost per drone (€)	1,000	500	100
Total investment cost (€)	174,567,524	106,153,545	61,291,162
Depreciation time (years)	7	7	7
Annual investment cost (€)	24,938,218	15,164,792	8,745,595
Number of operational days	292	292	292
Daily investment cost (fixed cost) (€)	85,405	51,934	29,951
Airspace cost per drone (€/hr)	2	0.50	0.25
Labour cost (€/hr)	30	20	20
Number of operators	1,455	582	291
Number of operational hours per day	7	7	7
Daily operational cost (€)	563,958	146,082	73,041
Total daily cost (€)	649,363	198,016	102,992
Delivery cost per meal order (€)	2.51	0.77	0.40

ANNUAL MAINTENANCE COST PER E-BIKE

This cost factor is based on the usage of the bike. Estimates for maintenance cost for an E-bike is obtained from ([57]) in which a range is specified for maintenance cost estimates between €180 - €105 per year. The highest cost from the range is employed for the conservative scenario which stands at €180 per year. Then, the average of the range, €142, is assumed for the high potential scenario. And finally, for the high acceptability scenario, the lowest cost of the maintenance cost range is assumed at €105 per year.

ANNUAL INSURANCE COST PER E-BIKE

The cost of insurance for theft and damage for E-bicycles are relatively low compared to drones. According to ([58]), insurance cost per E-bike can vary from €33 - €84 per year. For this study we assume the insurance cost for the conservative scenario to be €84 i.e., we assume the highest value from the above range. The average of the range (€58.5) is employed for the high potential scenario and the lowest value from the range, €33, is assumed to hold true in the high acceptability case.

LABOUR COST PER HOUR

This cost is mainly driven by the cost of employing couriers for operating the E-bikes and in delivering meal orders, which can be highly labour intensive. Quick-service restaurants generally employ delivery personnel between the ages of 16 and 17 years. This is evident in Europe. As a result, the cost of labour is relatively cheap since employers are not stipulated to meet the minimum wage threshold ([201]). We assume that the cost of labour for couriers to remain steady at €10 per hour for all three scenarios.

2.4.4. COMPARISON BETWEEN DRONE AND E-BIKE DELIVERY OF FAST-FOOD MEALS

The feasibility of delivering fast-food meals for 291 restaurant kitchens in Paris by a fleet of drones or E-bikes has been analysed for three different scenarios. Table 2.10 illustrates the different costs associated with delivering meal orders using a fleet of 18,458 drones to meet the hourly demand of 36,915 meal orders for the three scenarios. Based on these different costs, and the total fast-food demand of 258,408 meal orders per day, the delivery cost per individual meal order via a drone is presented (Table 2.10). For the conservative scenario, this delivery cost amounts to €2.51 per meal order. In the high potential case, the cost of delivery by drone is €0.77 per meal order. This is similar to the cost reported in ([103]), albeit for a small consumer package, which estimated the delivery cost to be approximately €0.79 per order via a drone.

In the high acceptability scenario, the drone-based delivery cost is estimated to be €0.40 per meal order. Compared to the conservative scenario, the high potential and high acceptability scenarios indicate a significant decrease in delivery cost. This is primarily attributed to the lower number of required drone operators due to the assumption of autonomous drone operations, which is expected

Table 2.11: E-bike food-delivery costs estimations for pessimistic, realistic and optimistic scenarios.

	Delivery E-bike		
Parameter	Conservative	High potential	High acceptability
Number of E-bikes	7,383	7,383	7,383
Cost of E-bike (€)	2,500	1,875	1,500
Cost of modification per E-bike (€)	150	100	50
Cost of extra battery (€)	100	50	25
Annual maintenance cost per E-bike (€)	180	143	105
Annual insurance cost per E-bike (€)	84	59	33
Total investment cost (€)	22,252,620	16,434,749	12,647,226
Depreciation time (years)	7	7	7
Annual investment cost (€)	3,178,946	2,347,821	1,806,747
Number of operational days	365	365	365
Daily investment cost (fixed cost) (€)	8,709	6,432	4,950
Labour cost (€/hr)	10	10	10
Number of couriers	7,383	7,383	7,383
Number of operational hours per day	7	7	7
Daily operational cost (€)	516,816	516,816	516,816
Total daily cost (€)	525,525	523,248	521,766
Delivery cost per meal order (€)	2.03	2.02	2.02

to be viable as technology progresses.

Table 2.11 illustrates the E-bike food-delivery costs for the three scenarios. In comparison to drone delivery, the annual investment cost for E-bike delivery is relatively low due to the lower cost of the E-bike. However, this benefit is outweighed by the daily operational cost that is caused as a result of labour intensive delivery trips. Unlike drones, E-bikes (or any road-based vehicle) are difficult to automate due to the high complexity of the ground-based environment, and the presence of high numbers of unpredictable dynamic obstacles. As a consequence, large numbers of fully automated aerial vehicles are sooner expected to be viable than large numbers of fully automated ground vehicles.

As seen in Table 2.11, wages paid to the (7,383) couriers represent the largest portion in the total daily operational expense. Since a conservative assumption is made for steady wages across all three scenarios, the delivery cost per meal order does not decrease across the three scenarios. For all three scenarios the E-bike food-delivery cost is between €2.03 and €2.02 per meal order. This cost range is in line with average delivery cost per order for large-scale quick-service restaurant chains ([137]).

The above analysis indicates the potential economic feasibility of using a fleet of autonomous drones to deliver meals from a cluster of McDonald's restaurants in Paris. The cost of operating a fleet of food-delivery E-bikes is nearly twice as more compared to drone-based delivery. As a result, large-scale quick-service restaurants such as McDonald's, could benefit from switching their food-delivery mode to high-speed drone delivery. In addition, the associated cost-savings could be passed onto the consumers, which will likely trigger further demand for the food-delivery service. The use of drone-based delivery may also alleviate some of the road traffic congestion arising from the traditional food-delivery modes. This results to a reduction of 7,383 E-bikes from the urban street network thus, increasing the level of safety for road-users.

Table 2.12: Expected traffic density of drone-based meal delivery drones in the Paris metropolitan area, with an area of $12,012\text{km}^2$, for three variant scenarios which forecast food-delivery growth at 0.9, 1.8 and 3.6 percent. Note the baseline year is 2019 for which 18,458 food-delivery drones were estimated in an area spanning $12,012\text{km}^2$.

Year	Low	Medium	High
2035	21,303	24,555	32,504
2040	22,279	26,846	38,791
2045	23,300	29,351	46,295
2050	24,367	32,089	55,250

Research by ([153]) indicate a 11 percent growth per year (between 2017 to 2022) in food-delivery for France. However, it is unlikely that such growth figures can be sustained until 2050. Therefore, we take a conservative estimate by assuming growth-rates of 0.9, 1.8 and 3.6 percent yearly, similar to the average economic growth, in the online food-delivery industry between 2035 and 2050. Hence, a forecast can be made for drone-based traffic density stemming from meal order deliveries for Paris (Table 2.12). The expected traffic density of drone-based meal orders by 2035 could potentially reach nearly 24,555 drones per hour in an area of $12,012\text{km}^2$. Therefore, to make drone-based food delivery viable, infrastructural, technological and legislative bottlenecks will need to be solved.

The physical infrastructure at restaurant kitchens currently supports the integration of E-bikes due to minimum infrastructure requirements. In order to handle fleets of delivery drones, off-site restaurants (see [32]) that exclusively focus on meal-deliveries, may prove to be more practical to integrate and operate food-delivery drones ([82]). However, safety concerns such as integrating take-off and landing pads (or docking stations) at restaurants situated in dense urban environments are yet to be investigated. Similarly, the integration of such take-off and landing pads and their associated drone charging stations may also require large financial investments which may not be attractive to quick-service restaurant operators. On the technological and legislative front, this potential can only be realised when the level of autonomy for food-delivery drones becomes matured, or as cognitive autonomy is achieved ([66]), thus requiring a lower number of operators, and when U-Space is fully capable of safely handling high-density drone traffic in VLL urban airspace. A summary of the above comparative analysis between drone delivery and E-bike food-delivery is presented in Table 2.13.

Table 2.13: Summary of comparative analysis for the two transport modes of fast-food meal delivery. We show the main advantages and disadvantages between drone-based delivery and E-bike delivery of fast-food meals which was gathered from the analysis.

Transport mode	Pros	Cons
Delivery drone	• Relatively easier to automate due to lower complexity of environment, and lower number of unpredictable dynamic obstacles. • Able to perform high-volume and high-speed delivery. • Helps reduce traffic congestion.	• Requires infrastructure changes for integration. • Delivery cost is dependent on the level of automation. • Requires high investment cost.
Delivery E-bike	• Existing infrastructure supports integration. • Requires low investment cost.	• Delivery cost is highly dependent on cost of labour. • Prone to high number of road accidents when high-speed delivery is required. • Delivery may get affected by traffic congestion. • Difficult to automate due to the presence of high number of unpredictable dynamic obstacles.

2.5. CHALLENGES FOR U-SPACE

U-Space is considered to be a key technology enabler for the execution of safe aerial missions such as food and express package delivery by drones. The U-Space program defines four progressive U-Space deployment levels: U1, which is a set foundation services to allow for drone registrations and identification; U2, consist of a set of initial services to enable safe administration and management of drone flights; U3, comprise of advance services to support high-density drone operations in complex environments; and U4, will integrate U-Space with current air traffic management and the capability of full autonomy ([172]). A comprehensive list of service for each U-Space deployment level is presented in Table 2.14.

Each of the U-Space level consists of a set services aimed at supporting and adopting the growth of drone operations for European Union (EU) member states. However, challenges associated with integrating high densities of drone traffic to the urban airspace in a safe and efficient manner, is yet to be tackled by the regulatory and technological apparatus of U-Space.

The question remains what would be the expected volume of drone traffic for a typical urban airspace such as Paris. The study conducted by ([5]) estimated an average of 16,667 delivery drones per hour, or a traffic density of 8,333 delivery drones, for Paris by 2035. The latter figure is nearly eight-fold lower than the potential scenario of traffic density delivery drones of 63,596 estimated in this study for both express parcel and food deliveries.

The current study gives an estimate of the potential for drone-based transportation based on all eligible deliveries, whereas in practice, adoption of this means of transportation may be more gradual. However, even a fraction of such traffic densities will place challenges for the urban airspace to efficiently accommodate this while maintaining an acceptable level of safety. In addition, the demand for package and fast-food delivery drones is located in dense urban areas which is inundated by several airspace constraints. First being the limitation of drone flights in urban areas to a thin altitude band, known as Very Low Level or VLL airspace which stipulates drones to fly between 0 and 500ft, above ground level. Second, urban areas are congested by heterogeneous (permanent and non-permanent) man-made and natural obstacles ([147]). For example, Paris city has more than 350,000 man-made permanent obstacles with varying heights, within an area of 105km^2. Urban areas are also prone to a high number of temporary and permanent No-Fly-Zones that prohibit drone flights over particular locations such as schools, parks, stadiums and government buildings, supported by geofences. The VLL airspace is also occasionally populated

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Table 2.14: U-Space services in U1, U2, U3, and U4 deployment levels, extracted from ([172]).

U-Space deployment level	**U-Space service**
U1: Foundation services	Registration; Registration assistance; E-Identification; Geo-awareness Drone aeronautical information management
U2: Initial services	Tracking; Surveillance data exchange; Geo-fence provision; Operation plan preparation; Operation plan processing; Risk analysis assistance; Strategic conflict resolution; Emergency management; Incident/accident reporting; Citizen reporting service; Monitoring; Traffic information; Weather information; Navigation/communication infrastructure monitoring; Legal recording; Digital logbook; Procedural interface with air traffic control
U3: Advanced services	Dynamic capacity management; Tactical conflict resolution; Geospatial information service; Population density map; Electromagnetic interference information; Navigation/Communication coverage information; Collaborative interface with air traffic control
U4: Full services	Integrated interfaces with air traffic control; Autonomous flight

by manned flight traffic, for instance general aviation aircraft, gliders and helicopters which further constrain the airspace for urban drone flights.

The expected volumes arising from express parcel and food delivery, combined with the various airspace constraints, presents major challenges for U-Space to optimally integrate high densities of drone traffic to the urban airspace. As high volumes of drone-based delivery missions begin to gradually unfold in the urban airspace, for several low-level (U1, U2) U-Space services, the load will scale linearly with the number of operations (number of registrations, number of information requests). However, since traffic complexity contains a quadratic component of traffic density (through e.g., conflict probability), the demand for high-level U3/U4 services such as dynamic capacity management and tactical conflict resolution will be unparalleled compared to our current situation of controlled airspace, and thus the implementation of such services will require a fundamentally different approach (see [88]). Hence U-Space policymakers and researchers should address such crucial challenges by developing adequate protocols and robust airspace design measures in order to enable safe high-density drone-based delivery missions.

2.6. CONCLUSION

Drone-based delivery of small consumer packages and fast-food meals has the potential to make a large contribution to transportation in urban areas. Drones represent an agile and sustainable transport mode for e-commerce companies and quick-service restaurants, especially when high-volumes of high-speed deliveries are required. Drone-based delivery may contribute to ease traffic congestion in our already congested urban cities. In this paper, we established a framework for estimating the drone-based package delivery traffic densities of five EU countries. This estimation is performed for three growth scenarios (0.9, 1.8 and 3.6 percent annual growth rates) between 2035 until 2050. From the list of five countries, a case-study is presented for Paris metropolitan area. The study predicts, for a 1.8 percent conservative growth rate, that the urban airspace of Paris would need to cope with a traffic density of 63,596 drone-based deliveries of small express packages as well as fast-food meals by 2035 within an area of 12,012km^2. The proposed method can be applied to any given city, albeit with suitable modelling assumptions. In addition, we presented a detailed analysis between an existing and a potential food-delivery transport mode. Our approach indicated a strong economic incentive to use a fleet of drones to perform food-delivery tasks. To be able to accommodate such traffic numbers, a robust airspace management system is required in order to realise commercial drone delivery.

3

CONSTRAINED URBAN AIRSPACE DESIGN

The results of the previous chapter indicated that the hourly traffic densities culminating from express packages as well as fast-food drone deliveries may exceed the current global commercial aircraft traffic by more than six-fold in just one city alone. To support such high densities of traffic in dense urban areas, a radically new airspace design is needed. Therefore, this chapter presents the design of two novel airspace concepts of a constrained urban environment. The two concepts bear resemblance to that of road-based design and thus having two-way and one-way streets by imposing horizontal constraints. For applicability, the concepts are applied to the street network of Manhattan, New York. The performance of these airspace concepts is compared and evaluated for multiple traffic demand densities in terms of safety, stability, and efficiency. The results reveal that an effective way to structure drone traffic in a constrained urban area is to have vertically segmented altitude layers with respect to travel direction as well as horizontal constraints imposed to the flow of traffic.

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3.1. INTRODUCTION

The current advancement in unmanned aerial vehicles, which is commonly referred to as drones, has potential applications in agriculture, research, inspection, health-care, urban air mobility [34, 43, 66, 70, 101, 105, 117], and logistics, especially in the transport of small express packages of consumer goods and fast-food meals within cities [81, 111, 128, 148]. Recently, this demand has been exemplified by commercial logistics companies conducting drone delivery test flights in dense urban areas [62, 116]. One reason for this interest is the potential environmental benefit [179] and the attractive economics of drone-based delivery [50, 51]. However, if the large-scale adoption of drone-based delivery does begin to unfold, safely organising such traffic in the low altitude urban airspace, which is highly constrained by existing street networks and buildings, will be one of the main challenges to overcome.

In order to cope with the future demand for drone-based services, previous research, such as the Metropolis project, has demonstrated that vertically segmenting the airspace in order to separate cruising traffic with respect to travel directions at different altitudes, leads to high levels of safety [183, 184]. The study revealed that two factors, segmentation of traffic and the reduction of relative velocities (i.e., alignment of traffic), between cruising traffic at the same altitude were the main contributors to lowering the conflict probability and, thus, an increase in airspace safety [89]. In a follow-up study, these principles were formalised in a concept, called Geovectoring, as a means to define airspace designs [88, 182]. However, all of these past studies have been limited to unconstrained airspace environments, which is, the airspace above buildings or free of any built-up areas.

Other recent studies have investigated different risk-based path-planning algorithms for drones in constrained urban environments [141, 151, 209]. Studies have also been done in finding the optimal three-dimensional (3D) paths with respect to the locations of charging stations for a limited number of drones in built-up areas [14]. While a fair amount of work has been done in proposing airway routes for drones in cities [209], they are mainly policy-based studies. Further, unmanned traffic management programs, such as U-Space, are supporting the use of four-dimensional (4-D) trajectory and detect-and-avoid technologies to navigate the urban environment [15].

This study will investigate approaches to structure the urban airspace to facilitate large-scale drone delivery traffic by applying the principles of traffic alignment and segmentation to a constrained urban area. For this purpose, two en-route urban airspace concepts will be presented: a two-way and one-way concept. By using fast-time simulations, the performance of the two concepts are compared for multiple traffic demand scenarios with respect to safety, stability, and efficiency metrics.

The research described in this study is performed within the context of a futuristic drone-based delivery mission. This is done in order to mimic one example of a potential scenario for autonomous flying entities operating in a constrained urban environment in high traffic densities, which allows for evaluating and comparing the two airspace concepts. Drone-based delivery is just one side of the spectrum of potential users of the urban airspace. There also exist other advanced air mobility candidates, such as flying taxis [101], which may also manifest in high traffic densities. Therefore, the aim of this research is not to provide an operational-ready urban airspace design solution for a particular type of drone; instead, the study focuses on the effect of high traffic densities and how it may influence the constrained urban airspace concepts.

The remainder of this chapter is structured, as follows: Section 3.2 outlines essential background material. Sections 3.3 and 3.4 present the methodology of the study. In particular, Section 3.3 describes the design of the two urban airspace concepts for constrained environments and Section 3.4 explains the simulation set-up that was used to compare the performance of the concepts. In Section 3.5, we present the results of the simulations. We then discuss the key findings, outline the limitations of the study, and present avenues for future research in Section 3.6. Finally, Section 3.7 summarises the main conclusions of this study.

3.2. BACKGROUND

In this section, a summary of relevant background material is presented. The section begins with a quick overview of common traffic structuring concepts found in manned aviation and road-based transport. Next, a description of the relationship between conflicts and intrusions is given. Thereafter, we discuss how traffic segmentation and alignment help to mitigate conflict probability and how they can be applied to a constrained environment.

3.2.1. AIRSPACE STRUCTURE

The function of airspace structure is to provide a priori separation and the organisation of traffic [181, 183, 184]. One example of an airspace structuring methodology that has been used in manned aviation in the past is the hemispheric rule [67, 94]. The rule ensures that cruising aircraft above flight level FL240, with respective travel directions in ranges of 000–089° and 090–179°, are assigned to odd flight-levels in multiples of 10, while cruising aircraft with headings between 180–269° and 270–360° are also allocated to fly at even flight-levels in multiples of 10 [67, 94]. Similar to the hemispheric rule, there also exists a more finer-grained airspace concept known as the quadrantal rule, which is enforced within the altitude range of 3000 ft to FL240 [67]. In the quadrantal rule, aircraft with headings between 000–089° are required to fly at odd altitudes in multiples of 1000 ft, while aircraft with headings 090–179° are instructed to also fly at odd altitudes in multiples of 1500 ft [67]. Similarly, flights with headings between 180–269° must utilise even altitudes in multiples of 1000 ft, while flights with headings in the range of 270–359° are allocated to fly at even altitudes in multiples of 1500 ft [67]. Both methods of airspace structure lead to lower conflict probability and thus higher airspace safety and capacity. Note that the hemispheric rule is similar to the 'layers' airspace concept in the Metropolis study, which promoted traffic alignment and segmentation [183, 184].

3.2.2. ROAD AND STREET STRUCTURE

Road and urban street networks contain a great deal of structure that is largely shaped by the physical layout of cities [16]. Current road and street networks are primarily structured with channelisation planes, which define flow paths for traffic using road markings, islands, and raised medians [38]. Such structuring modes help to lower the occurrence of conflicts, especially at intersections where conflicts are widely prevalent [38, 68]. These measures also help to define and segregate two-way and one-way streets (see Figure 3.1), which are proven techniques for increasing the safety and throughput of the street network [38, 72].

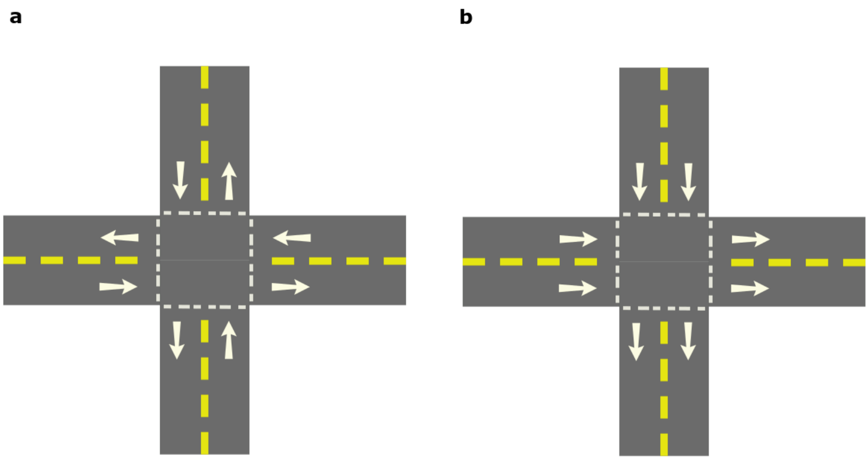

Figure 3.1: Typical intersection configuration for road-based traffic. (**a**) Two-way network. (**b**) One-way network. Note that the arrows depict the direction of traffic flow.

3.2.3. CONFLICTS AND INTRUSIONS

The number of conflicts and intrusions are important metrics that describe the safety of an airspace. An intrusion, i.e., a loss of separation, occurs when the separation requirements, both in the horizontal and vertical plane between aircraft, are violated. In contrast, a conflict, which is defined as a predicted loss of separation, occurs when the horizontal and vertical separation distances between two aircraft, in this case, drones, are expected to be less than the established separation requirements within a prescribed 'look-ahead' time. This means that a conflict is an expected/anticipated intrusion (see Figure 3.2).

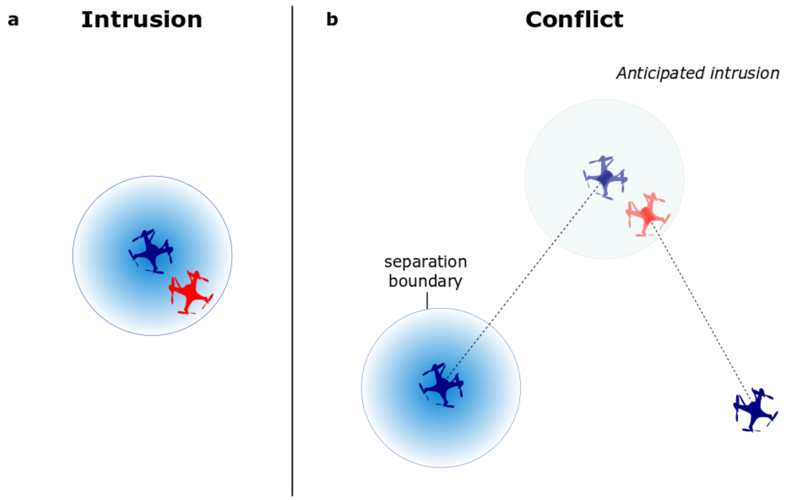

Figure 3.2: Difference between intrusions and conflicts between two drones in the horizontal plane. (**a**) An intrusion occurs when there is a violation of the separation boundary. (**b**) A conflict is an anticipated or predicted intrusion.

3.2.4. TRAFFIC SEGMENTATION AND ALIGNMENT

The effect of traffic segmentation and alignment can aptly be described while using the mathematical combinatorics that are expressed by Equation (3.1), which has been extensively validated in recent airspace studies [88, 89].

$$CR_{global} = \frac{1}{2}N(N-1)p_2 \tag{3.1}$$

Using the above equation, it can be seen that, for a given volume of airspace, increasing the number of possible drone combinations (N) causes a quadratic increase in the global conflict rate (CR) or conflict probability. Increasing the probability of conflict of possible drone combinations (p_2) increases CR linearly.

The parameters N and p_2 influence the conflict probability of the airspace structure. Therefore, the conflict probability can be mitigated by effectively decreasing N and p_2. The former is achieved by the segmentation of traffic, while the latter is primarily done by reducing the relative velocities of cruising drones in order to promote traffic alignment [89]. Note that segmentation, as well as relative velocity reduction, have a linear relationship with conflict probability [89]. Therefore, simultaneously influencing the parameters of N and p_2 will have a greater impact to the conflict probability.

3.2.5. CONSTRAINED URBAN AIRSPACE

Past research have applied the principles of segmentation and alignment to a unconstrained or free airspace [183, 184]. However, the very low altitude urban airspace, where drones are expected to operate, contains operational complexities, due to the presence of dynamic and static obstacles as well as temporary and permanent no-fly-zones [147]. This part of the airspace is also frequently occupied by general aviation aircraft and helicopters. Therefore, the urban airspace is heavily constrained when compared to manned aviation airspace. Nevertheless, many of these operational complexities (and their characteristics) are shared by ground-based traffic, for which there exists a wide body of literature [38, 71, 113, 176].

Similar to road vehicles, drones can employ existing street networks and, thus, 'fly-over-streets' in constrained urban spaces. However, with the expected large-scale drone traffic volumes, simply flying over streets may not be adequate to ensure airspace safety. When drones fly in competing travel directions in a constrained environment, a large number of conflicts would be triggered, due to high average relative velocities and limited flexibility of the airspace. As a result, applying segmentation and alignment principles to this portion of the airspace, in particular, would organise traffic into different altitude layers with respect to travel directions and, thus, add more structure to the constrained environment.

3.3. DESIGN OF URBAN AIRSPACE CONCEPTS FOR CONSTRAINED SPACES

In this section, the motivation to fly-over-streets in constrained urban areas is first presented. Before describing the airspace concepts, key observations from the initial experiments are revealed. Thereafter, the section describes and compares the two urban airspace concepts for a constrained environment.

3.3.1. FLYING OVER STREETS

Extrapolating from the research study of Metropolis [183, 184] and urban street network studies [29, 72, 139], we developed a two-way and a one-way airspace configuration. In this sense, the flight routes adhere to the urban street network, i.e., the drone flights are directly guided along the streets. The two-way concept has no horizontal constraints that are imposed to the flow of traffic, while the one-way concept contains horizontal constraints to achieve one-way directional flow. In both concepts, the airspace is vertically segmented to form a stack of altitude layers for which traffic is organised in accord to north, east, south, and west directions, which are also known as the cardinal directions.

Having drone flights follow existing street networks offers two main benefits. The first being the relatively lower risk of privacy concerns as drones will not directly fly over private properties. Second, existing parcel transportation modes, such as trucks and vans, can potentially work in tandem with delivery drones in urban areas in order to optimise the last-mile delivery schedule [4].

3.3.2. PRELIMINARY INVESTIGATIONS AND KEY OBSERVATIONS

TURNING FLIGHTS

By applying the two airspace concepts to an actual urban network, our initial trial experiments indicated a strong association between the turning radii at intersections in the urban network and the performance of the drone. Because our initial experiments incorporated a constant drone cruise speed (10.3 m/s) and bank angle (35°), the trial simulations showed that, when drone flights maintained its cruise speed while executing turns, it caused the drones to deviate from their actual route. In order to address this challenge, the initial investigations revealed the need for drones to decelerate by at least 50 percent (i.e., 5 m/s) of its respective cruise speed in order to safely execute the turns.

THROUGH AND TURN ALTITUDE LAYERS

To cope with turning flights that require reducing speed to perform safe turns, transition or so-called turn altitude layers are included in both airspace concepts. Therefore, the use of turn altitude layers helps to separate through traffic from turning traffic. In this study, through traffic is defined as the traffic that travels across at least one intersection, while turn traffic is composed of traffic that is turning at an intersection and thus decelerating in order to safely execute the turn. Note that the allocation of the through traffic and turn traffic into different altitude layers mitigates any disruption to the flow of traffic. Consequently, it reduces the probability of conflict between the slow turning traffic and through traffic, which increases the airspace safety. A similar design philosophy is employed in road design to distinguish between different types of traffic on the highway [71].

In the current study, the two-way and one-way airspace concepts both consist of multiple stacks of altitude layers that range from 75 to 1050 ft. Furthermore, the concepts feature through and turn-layers that are vertically spaced at 25 ft, while through-to-through and turn-to-turn layers are spaced at 50ft, respectively, as illustrated in Figure 3.4. Of note, we use the current altitude range in this study, as policymakers in U-Space are yet to define the boundaries of low-altitude airspace [15]. This is because future operations, such as urban air mobility and other drone operations, may require much higher altitude boundaries than what has been initially defined [15].

3.3.3. CONCEPT DESIGN FEATURES

Drone traffic is segmented within altitude layers that are defined between 75 and 1050 ft with respect to their travel directions. Each altitude layer is separated with a vertical distance of 25 ft, as mentioned previously. This means that both concepts hold 40 altitude layers, which comprise of 20 through-layers and 20 turn-layers, respectively (see Figure 3.4). Further, both concepts assign flights with shorter trip distances to lower altitudes, while flights with longer travel distances are allocated to higher altitudes.

TWO-WAY

The traffic in the altitude layers of the two-way airspace concept is organised with respect to a heading range of 90°. This allows for traffic with flight headings (ψ) to be assigned to flight levels accommodating the four cardinal directions, as shown below:

- $315° < \psi \leq 045°$: North bound layers
- $045° < \psi \leq 135°$: East bound layers
- $135° < \psi \leq 225°$: South bound layers
- $225° < \psi \leq 315°$: West bound layers

The two-way airspace concept comprises of a total of 40 altitude layers consisting of both through and turn layers. In this concept, 10 layers are assigned for each of the four directions (Figure 3.4). The segmentation of traffic in this concept prevents opposite flows of traffic from interacting at the intersections (Figure 3.3). In this airspace system, short flights are assigned to low altitudes, while longer flights are allocated to higher altitudes. In order to allocate these cruising altitudes, we use the following heading-altitude rule, adopted from [181]:

$$h_{TW,i} = h_{min} + \zeta \left[\left[\frac{d_i - d_{min}}{d_{max} - d_{min}} \kappa \right] \beta + \left[\frac{\psi_i}{\alpha} \right] \right] \tag{3.2}$$

The heading-altitude rule that is described by Equation (3.2) is a function of the drones' heading ψ_i, its optimal flight path distance, d_i, and the minimum and maximum origin-destination (note that the origin is one of the depot location) distance threshold (d_{min} and d_{max}), which is defined at 1 km and 10 km, respectively. The remaining constants are the heading range per flight level, α, which is equal to 90°; the minimum altitude of the through-layer, h_{min} (i.e., 100 ft); β, which is equal to 4 (i.e., 360°/ α); κ as 5; and, the vertical distance (ζ) between through-through-layers, which is equal to 50 ft.

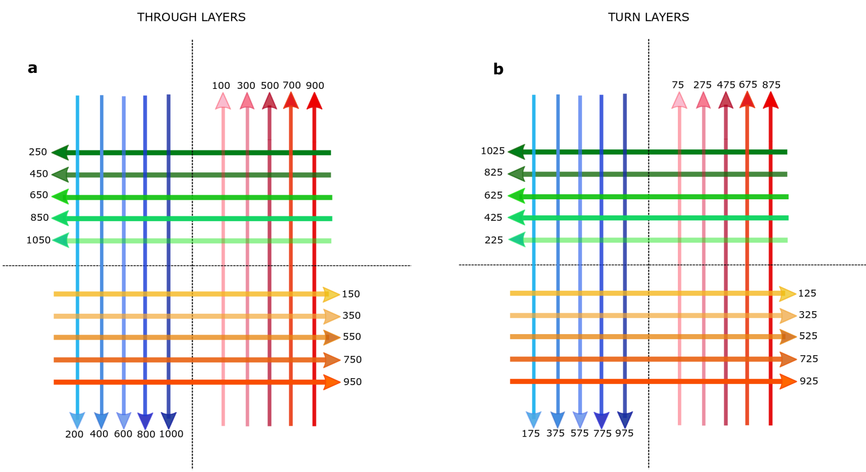

Figure 3.3: Traffic flow at a typical four-leg intersection for the two-way airspace concept. The traffic is vertically segmented into different altitudes with respect to their travel direction. Note that the altitudes are presented in ft. (**a**) Altitude layers belonging to the through traffic, which 20 altitude layers consist. (**b**) Altitude layers allocated for turn traffic, which consist of 20 individual altitude layers. Of note, the through-layers accommodate traffic that pass through at least one intersection, while turn-layers accommodate traffic that is decelerating to make a turn at the intersection. Recognise that opposite traffic flows do not intersect at the intersection.

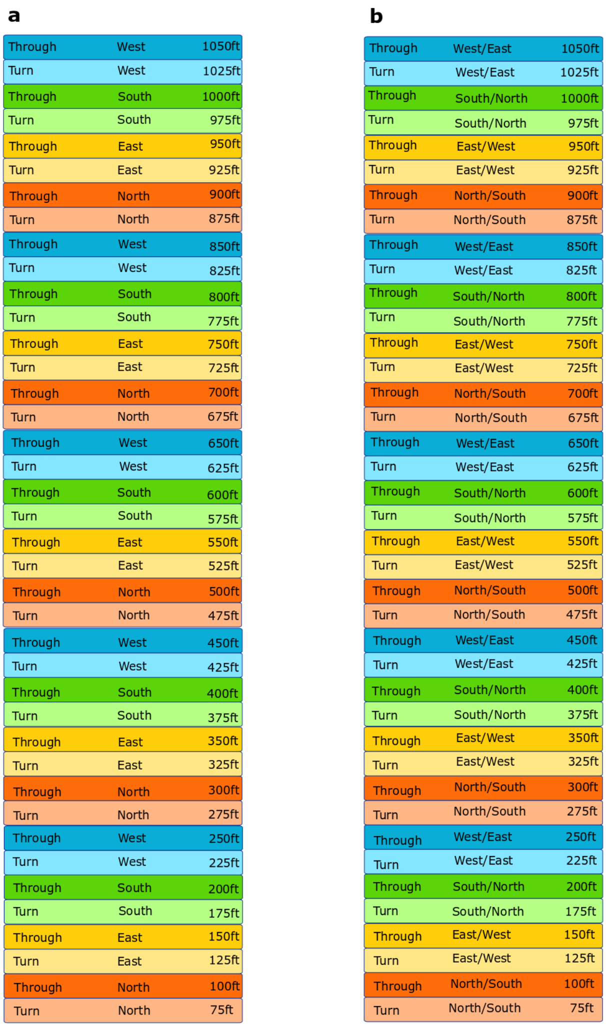

Figure 3.4: Schematic view for the complete set of altitude bands for the two urban airspace designs, where each altitude layer corresponds to its respective travel direction. Each concept has 40 altitude layers (which consist of 20 altitude layers allocated for through traffic and 20 altitude layers for turn traffic) from 75 to 1050 ft with a vertical spacing of 25 ft, respectively. The turn-layers are used for transitory flights, that is, drones that need to make turns/change direction at intersections. While the through-layers are utilised by through traffic, that is traffic passing through at least one intersection. (**a**) The two-way concept layer system for which traffic is allocated to the cardinal directions with respect to flight headings(ψ): 315° $< \psi \leq$ 045° headings assigned to north; 045° $< \psi \leq$ 135° headings to east; 135° $< \psi \leq$ 225° headings to south; and 225° $< \psi \leq$ 315° to west bound traffic. (**b**) One-way layer system where traffic with flight headings: 315° $< \psi \leq$ 045° and 135° $< \psi \leq$ 225° are assigned to north and south layers; and, traffic with flight headings between 045° $< \psi \leq$ 135° and 225° $< \psi \leq$ 315° are allocated to the east and west bound altitude layers. Of note, recognise that, when compared to the two-way concept, the one-way concept has north/south and east/west traffic assigned to one altitude layer, for which the separation of this traffic is assured by the spatial geometry of the urban street network.

3

ONE-WAY

The one-way concept consist of 40 altitude layers consisting of both through and turn traffic layers (see Figure 3.4). In this concept, horizontal constraints are imposed to the direction of travel in order to promote one-way traffic flow. The enforcement of the horizontal constraints culminates in uni-directional traffic flow over a single street. Therefore, a street will either accommodate north, east, south, or westbound traffic, depending on the direction of travel of flight and the use of the one-way directional constraint. This sets the one-way concept apart from the two-way concept, where opposing traffic flows occupy the same street, although in different altitude levels. Thus, the prohibition against having opposing traffic flow within a single street in the one-way concept allows for an additional set of altitude layers to be assigned for uni-directional travel. As a result, twice as many altitude layers per cardinal direction can be assigned to the one-way concept. This means that, in the one-way concept, there exist 20 altitude layers for each cardinal direction as compared to the two-way concept, which has 10 altitude layers per cardinal direction. In order to accommodate the higher number of layers per cardinal direction, the opposite traffic flows are not separated by means of altitude. Instead, the separation is assumed to follow the spatial order of the urban street network, which is comparable to road-based traffic. Similar to the two-way concept, the altitude layers of the one-way airspace concept is also structured with respect to the heading range of 90°, albeit with 10 additional layers per cardinal direction. Therefore, 20 through and turn layers are allocated to each of the four cardinal directions, which allows for traffic with flight headings (ψ) to be assigned, as follows:

- $315° < \psi \leq 045°$: North bound layer
- $045° < \psi \leq 135°$: East bound layer
- $135° < \psi \leq 225°$: South bound layer
- $225° < \psi \leq 315°$: West bound layer

Figure 3.5 illustrates an example of the traffic flow and its combination of altitude layers at a typical four-leg intersection. The similarity of the direction of the traffic flow can be compared to that of the one-way road-based intersection that is shown in Figure 3.1. In addition, the properties of one-way network configuration enables a typical four-leg intersection to only accommodate two directions of traffic flow, which is south and east bound traffic, see Figure 3.5. Note that the remaining traffic flow directions are incorporated into adjacent intersections within the one-way network.

Despite this, the design of the one-way concept ensures that traffic from different directions do not mix at intersections (Figure 3.5). Furthermore, a simple altitude-heading rule (Equation 3.3) was used to compute the respective cruising altitudes ($h_{OW,i}$):

$$h_{OW,i} = h_{min} + \frac{h_{max} - h_{min}}{d_{max} - d_{min}}(d_i - d_{min}) \tag{3.3}$$

Once the cruising altitude per street edge is determined while using the above equation, a simple heuristic is used to ensure the altitudes of the flights are aligned according to their respective heading direction, ψ, as denoted by Algorithm 1:

Algorithm 1: Heuristic to align flight altitudes to their travel direction.

if $315° < \psi \leq 045°$ or $135° < \psi \leq 225°$ **then**
  $h_{OW,i} = h_{OW,i}$
else
  if $045° < \psi \leq 135°$ or $225° < \psi \leq 315°$ **then**
    $h_{OW,i} = h_{OW,i} + \zeta$
  end if
end if

In Equation 3.3, h_{max} and h_{min} are the maximum and minimum altitude level of the through-layer, d_i is the optimal path, and d_{min} and d_{max} are the minimum and maximum threshold distance to the respective origin-destinations. This equation ensures that shorter flights are allocated to lower altitudes and longer flights are allocated to higher altitudes, respectively.

3.3.4. CONCEPT COMPARISON

The main difference between the concepts is that the one-way concept has half as many roads available to each cardinal travel direction, albeit with twice as many vertical layers, when compared to the two-way concept. As a result, opposing traffic shares the same flight level, and it is separated by the street layout. Further, the two-way concept has more horizontal distribution of traffic and, therefore, there is no opposite traffic flows on the same altitude layers. Table 3.1 summarises the main comparisons between the two-way and one-way urban airspace concepts.

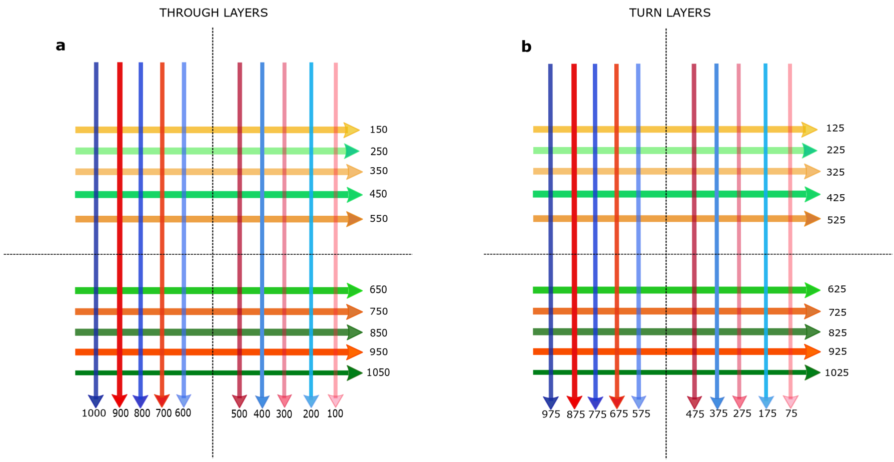

Figure 3.5: Traffic flow at a typical four-leg intersection for the one-way airspace concept. The traffic is vertically segmented into different altitudes with respect to their travel direction. Note that the altitudes are presented in ft. (**a**) Traffic flows belonging to the through-layers, which consist of 20 layers in total. (**b**) Traffic flows of the turn-layers, which consist of a total of 20 layers. The through-layers accommodate traffic that pass through at least one intersection, while turn-layers accommodate traffic that is decelerating to make a turn at the intersection. Note that opposite traffic flows do not intersect at the intersection.

Table 3.1: The main pros and cons of the two-way and one-way urban airspace concepts.

Concept	Advantages	Disadvantages
Two-way	• Flight-plans do not have to obey one-way directional constraints and thus no forced horizontal distribution.	• Traffic has less vertical layers per cardinal direction.
One-way	• Better airspace utilisation due to additional layers per cardinal direction. • Due to the imposed horizontal constraints, opposite traffic flows are spatially separated.	• Flight routes may be less efficient due to the imposed one-way directional constraints.

3.4. SIMULATION DESIGN

The two airspace concepts will be compared in a set of fast-time simulations, in terms of safety, stability, and efficiency. This section describes the design and development of these fast-time simulation experiments.

3.4.1. SIMULATION DEVELOPMENT

SIMULATION PLATFORM

The open-source Air Traffic Management simulator BlueSky [27, 85] is used as the simulation platform in order to conduct fast-time simulation experiments in this research. The BlueSky traffic simulation tool has been widely used in past ATM related [181, 183, 184]. For the purpose of this study, the tool is adapted to include the elements of the urban airspace concepts. This includes suitable drone models and updating BlueSky's autopilot module to account for the safe manoeuvrability of drones within the urban layout.

Most of the package delivery drone prototypes that are depicted in the media mainly appear to be multi-copters [47, 78, 111]. A reason for this may be linked the copters' agility and manoeuvrability, which allows for it to effectively navigate the complex urban landscape. Therefore, assuming the same trend continues into the foreseeable future, we employ the DJI Matric 600 Pro hexacopter drone model in this study. Table 3.2 presents the characteristics of the drone model.

Table 3.2: Performance data for DJI Matrice 600 Pro used in the simulations of this study.

Parameter	**DJI Matrice 600 Pro**
Speed [m/s]	5-10.3
Vertical speed [m/s]	-5-5
Mass [kg]	15
Maximum bank angle [°]	35
Acceleration/deceleration [m/s^2]	1.5

TESTING REGION

In this study, we investigate the performance of the urban airspace concepts on the urban street network of Manhattan, New York City, as shown in Figure 3.6. The reason for choosing Manhattan is three-fold. First, Manhattan has an orthogonal or grid-like spatial order, which contains fewer dead-ends, more four-way intersections, as well as less-winding street patterns [29]. In comparison to neighbouring cities, such as New York city and Staten Island, or European cities, such as Amsterdam or Paris, the low entropy and highly-ordered grid-like street orientations of Manhattan [30, 75] limit any sort of ambiguity in our findings. Second, newly constructed streets are increasingly grid-like [16, 17, 19]. Thus, the outcome of the current study would still be valid for future urban street networks. Third, recent urban air mobility studies have also utilised the Manhattan street network as a testing region in their experiments [154, 155].

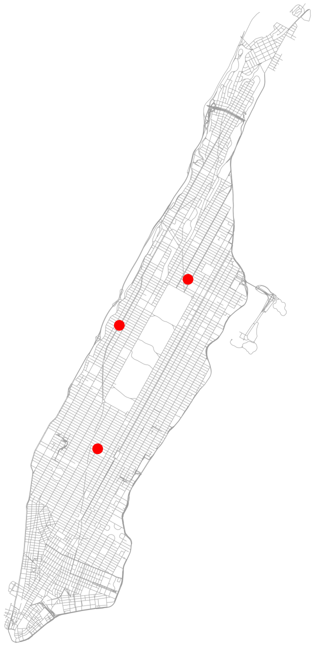

Figure 3.6: Urban street network of Manhattan, New York City (with area size of 59.1 km^2), obtained from OpenStreetMap via OSMnx Python library [28]. The three red dots represent the (approximate) location of the chosen drone depots in our study.

CONFLICT DETECTION AND RESOLUTION

The two urban airspace concepts relied on a 'state-based' conflict detection method for identifying any potential separation violations. The conflict detection was done by performing a linear extrapolation of the drone positions within a predefined 'look-ahead' time. However, the use of a linear extrapolation method means that false conflicts would need to be identified in the post-processing phase. Furthermore, the separation requirements of 164 ft horizontally and 25 ft vertically were respectively used in this study. Once conflicts were detected, a basic (1-D) speed control algorithm was used in order to resolve conflicts in a pair-wise manner. Of note, the horizontal separation requirement of 164 ft was adopted in this research, as it was also used in a recent UAV tactical conflict resolution study [157]. In terms of the vertical separation, a range of values have been employed in past studies [8, 33, 162, 205]. However, based on initial test simulations, the vertical separation of 25 ft was found to be suitable for the experiments.

URBAN AIRSPACE CONCEPT IMPLEMENTATION

The data to construct the street network of Manhattan were obtained from OpenStreetMap, while using the graph-based method in [28]. Separate graphs were generated for each airspace concept. The graph network of the two-way concept was made by creating an undirected graph that neglects the direction of the edges, while the one-way concept featured a directed graph that enforces the direction of the streets to be one-way. Subsequently, for both concepts, three depot locations (see red circles in Figure 3.6, where all of the drone flights depart from one of the three depots during the simulation) were selected based on initial experiments that promoted traffic flow convergence. For each depot, random destination locations were selected. To adhere to the range limits of the drone model, the random destination locations were further pruned out in order to meet a minimum and maximum distance of 1 km and 10 km, respectively. Afterwards, for each depot and its respective random destinations, we compute the shortest paths using the method in [76]. The generated shortest paths, consisting of a set of geographical coordinates, are then used to determine the bearing (heading direction) of the streets of each shortest path and the distance of the shortest paths. Subsequently, the cruising altitudes are computed using the heading-altitude rules that are described in Section 3.3.3.

Given the above flight-plan data, we will assess the location of turns in order to allocate the transition altitudes for the respective flights. This allows the drone flights to descend and decelerate in order to safely turn, within the transition altitude. The generated scenario of flight-plans, comprising of way-points, heading, altitude, and speed were then imported into BlueSky in order to perform fast-time simulations.

3.4.2. INDEPENDENT VARIABLES

The experiment in this study featured three independent variables:

1. urban airspace concepts: two-way and one-way designs;
2. airborne separation assurance conditions: with and without tactical conflict resolution; and,
3. traffic demand: low, medium, and high traffic densities.

Here, traffic demand levels are based on the food-delivery scenarios that are described in [51]. Table 3.3 summarises the resulting traffic demand scenarios.

Table 3.3: Traffic density characteristics of the three demand scenarios for the simulation area of Manhattan, New York City, network consisting of an area of 59.1 km^2.

	Low	**Medium**	**High**
Traffic density (drones/km^2)	55	61	73
Inflow rate (drones/min)	54	60	72
Hourly demand (drones/h)	3240	3600	4320
Demand per depot (drones/depot)	1080	1200	1440

The combination of these three independent variables results in 12 experiment conditions. For each experiment condition, five repetitions were done, which resulted in 60 simulations runs (two airspace concepts × two conflict resolution conditions × three traffic demand scenarios × five repetitions). Note that, for each simulation run, uniformly random destinations (between 1 km and 10 km) were used, thereby creating different trajectories with every individual simulation run.

3.4.3. DEPENDENT MEASURES

Dependent measures are considered in following categories: safety, stability, and efficiency, which includes throughput (or rate of arrivals of drones at its respective destinations), average number of turns per flight, and cumulative travel time.

SAFETY

The safety of the urban airspace is measured in terms of the number of conflicts and intrusions. An intrusion (loss of separation) occurs when the minimum vertical and horizontal separation requirements are violated, as explained in Section 3.2.3. A conflict is a predicted intrusion within the prescribed look-ahead time. Based on trial experiments, a look-ahead time of 30 s was chosen for this study, as it demonstrated the optimum balance between the number of false conflicts detected and the number of intrusions prevented.

STABILITY

The stability of the urban airspace refers to the potential for the creation of new conflicts that are caused by the conflict resolution manoeuvres as a result of the scarcity of airspace. This effect on the airspace has been measured in past research studies using the Domino Effect Parameter (DEP) [99, 112, 183, 184]. The

DEP can be calculated as follows:

$$DEP = \frac{C_w}{C_{wo}} - 1 \tag{3.4}$$

where C_w represents the number of conflicts with conflict resolution enabled and C_{wo} is the number of conflicts without conflict resolution. Note that a larger positive DEP value indicates a higher de-stabilizing airspace concept.

THROUGHPUT

The throughput metric measures the number of drones that arrive at its respective destination per minute. In particular, the throughput metric is used to describe the traffic outflow rate with respect to the accumulation of traffic for both airspace concepts. As drones depart from their respective depots, at a steady inflow rate, the traffic density will begin to slowly increase. As consequence, a higher proportion of drones will begin to slow down in order to avoid conflicts and, thus, the drones will spend a higher proportion of its time traversing the airspace, which would result in a lower throughput.

AVERAGE NUMBER OF TURNS

The efficiency of the concepts is also assessed while using the average number of turns per flight and the cumulative travel times. Similarly, studies that are related to on-ground transport have employed the notion of the average number of turns to explain the traffic dynamics of two-way and one-way street networks [72, 139]. In the current study, the number of turns per flight is expected to influence the performance of the airspace concept. This is because drones are subjected to lower flight speeds when turning. Even though the airspace concepts have turn-layers to accommodate these turning flights, it is likely that in-trail conflicts would be triggered, especially when two or more flights use the same intersection to perform the turns.

CUMULATIVE TRAVEL TIME

As a consequence of these lower flight speeds, drone travel times may get prolonged and, thus, result in additional conflicts. Therefore, this is captured by the cumulative travel time metric for both concepts, for low, medium, and high traffic demand.

3.4.4. EXPERIMENTAL HYPOTHESES

It is hypothesised that, as traffic demand increases from low to high, the safety, stability, and efficiency metrics will become worse. Therefore, we anticipate to see a greater number of conflicts, intrusions, and conflict chains as traffic demand increases. Furthermore, the one-way concept has twice as many altitude layers and, thus, greater vertical segmentation of traffic distribution, which further reduces the number of possible drone combinations per layer than the two-way concept. For these reasons, we expect the greater vertical segmentation and the horizontal structure to further reduce the probability of conflict when compared to the two-way concept. As a result, it is hypothesised that the one-way concept would have better performance with respect to safety and stability.

In terms of efficiency, it is hypothesised that the one-way concept would have higher traffic throughput than the two-way concept. The one-way concept has additional altitudes layers allocated per cardinal direction and, thus, more traffic flow can be accommodated. Further, it is hypothesised that the one-way concept would result in a higher number of turns per flight than the two-way concept. This hypothesis was developed with support from street network studies (see [72, 139]). Similarly, it is hypothesised that the one-way concept would result in greater cumulative travel times when compared to the two-way concept. Because one-way streets contain more circuitry than two-way streets, greater travel time to reach a particular destination can be expected [72, 113, 139].

3.5. RESULTS

This section presents the results of the experiment conducted in this study. The effect of the independent variables on safety, stability, and efficiency is presented using box-and-whisker plots. All of the box-and-whisker plots display the median line; interquartile range (IQR), which is represented by the boundary of the box; the minimum and maximum distribution of the data is marked by the whiskers; and, the points greater than $\pm 1.5\times$ IQR denote the outliers. Furthermore, the results for throughput efficiency of each urban airspace concept is presented while using scatter plots.

3.5.1. SAFETY

Figures 3.7 and 3.8 display the total number of pairwise conflicts and intrusions for each urban airspace concept, with respect to the three traffic demand cases. Note that independent of its duration, a pairwise conflict and intrusion is accounted only once during the simulation while a repeating pairwise conflict and intrusion is recounted. Figure 3.7 shows an increase in the total number of conflicts with traffic demand for both airspace concepts. The same trend is observed for the total number of intrusions (Figure 3.8). As hypothesised, the figures indicate that the two-way concept has a higher number of conflicts and intrusions than the one-way concept.

Furthermore, the figures show the effect of tactical conflict resolution for each airspace concept. The results with conflict resolution enabled describe the safety of the urban airspace concept, while the results with conflict resolution switched off indicate the level of conflict prevention. As expected, the results without tactical conflict resolution show that the one-way concept is able to circumvent conflicts from occurring, thus indicating higher intrinsic safety when compared to the two-way concept. For both airspace concepts, the number of intrusions significantly decreased with conflict resolution switched on. Despite this decrease in the number of intrusions, the same trend was not seen for the total number of conflicts. For both airspace concepts, the number of conflicts increased with conflict resolution switched on. This was primarily caused by the highly constrained airspace nature that resulted in less flexibility for resolution manoeuvres. As a consequence, the probability of encountering other drones was increased, which ultimately lead to conflict chain reactions. This notion was further examined by the airspace stability metric.

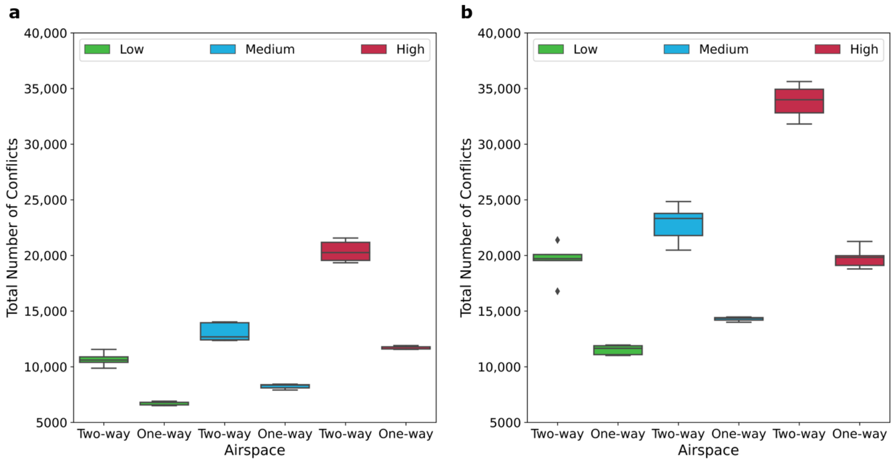

Figure 3.7: The total number of pairwise conflicts for the two-way and one-way urban airspace concept for low, medium, and high traffic demands. (**a**) Without conflict resolution. (**b**) With conflict resolution. Note that an intrusion is defined as a violation of the separation boundary while a conflict is a predicted intrusion.

3.5.2. STABILITY

The airspace stability is measured via the Domino Effect Parameter (DEP) [99, 112]. A high DEP indicates the presence of conflict chain reactions, thus causing

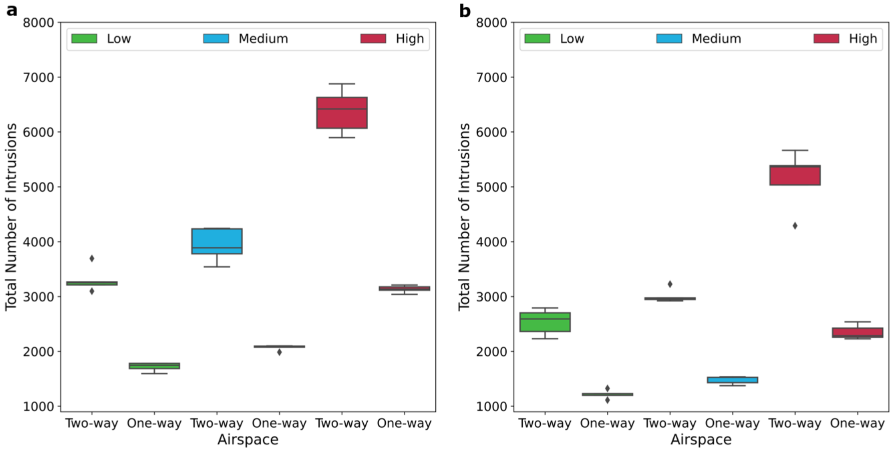

Figure 3.8: The total number of pairwise intrusions for the two-way and one-way urban airspace concept for low, medium, and high traffic demands. (**a**) Without conflict resolution. (**b**) With conflict resolution.

the airspace to become unstable. Figure 3.9 depicts the DEP values. Notably, the range of DEP values of the one-way concept are slightly lower when compared to the two-way concept, hence indicating a lesser destabilising effect. This trend was also observed in the number of conflicts (see Figure 3.7). In all conditions, the DEP values are close to one, which indicates that each resolution of a conflict, on average, triggers, at-most, one additional conflict. Contrary to expectations, no effect of traffic density on stability is observed.

3.5.3. THROUGHPUT

The number of drone arrivals per minute are determined by the rate of traffic demand (Figure 3.10). It can be seen that the rate of arrival has an upward trend from low to high traffic demand with and without conflict resolution for the two-way and one-way airspace concept. However, on the contrary to the experimental hypothesis, however, both airspace concepts demonstrate similar rate of arrivals for each traffic demand category (Figure 3.10). This increase in the rate of arrivals across the three traffic demand levels indicates that the network has not reached its maximum capacity [120]. In other words, traffic flow in both concepts is not congested.

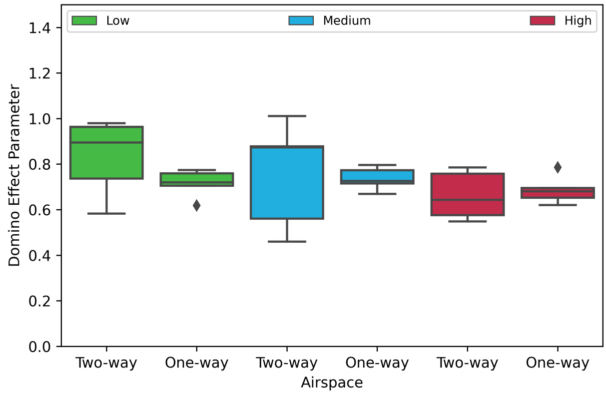

Figure 3.9: Domino Effect Parameter (DEP) for the two-way and one-way urban airspace concept for low, medium and high traffic demands. Note that the one-way concept have slightly lower DEP values as compared to the two-way concept.

3.5.4. AVERAGE NUMBER OF TURNS

Figure 3.11 presents the number of turns per flight-plan for both airspace concepts. Interestingly, for uniformly distributed trip distances, the two-way airspace concept contained slightly more than eight turns per flight-plan while the one-way concept had close to six and a half turns per flight-plan, on average.

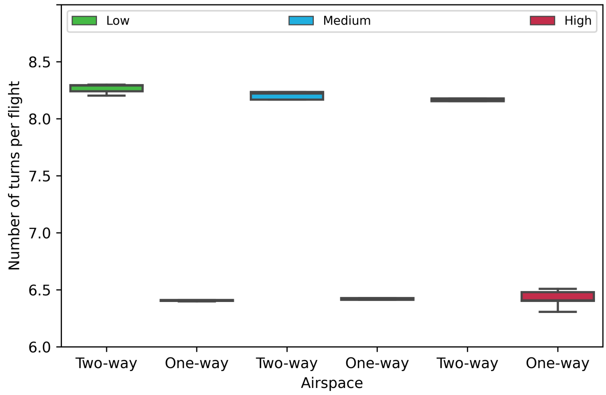

Figure 3.11: The number of turns per cumulative flight-plan for the two-way and one-way urban airspace concept.

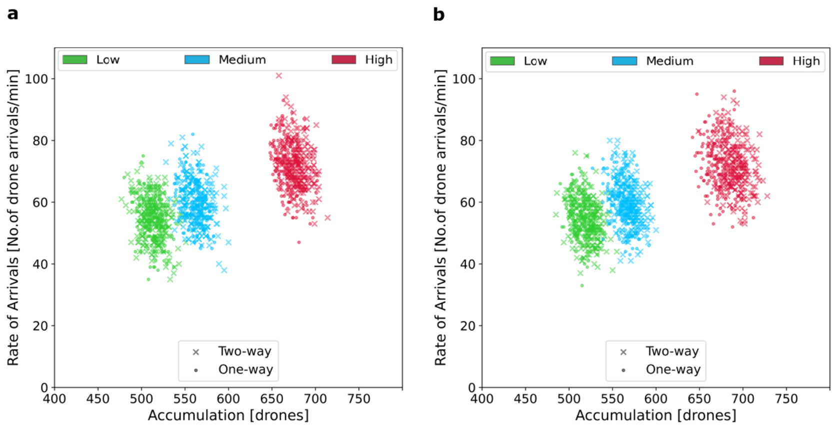

Figure 3.10: Rate of arrival for the two-way and one-way urban airspace concept for low, medium and high traffic demands. Each point represents the number of drone arrivals per minute. (**a**) Without conflict resolution. (**b**) With conflict resolution.

3.5.5. CUMULATIVE TRAVEL TIME

The relatively higher number of turns, between the two-way and one-way concept, had no significant impact on the cumulative travel times, as illustrated in Figure 3.12. In addition, the cumulative travel times showed no significant difference with and without conflict resolution (Figure 3.12). Both concepts demonstrate similar cumulative travel times.

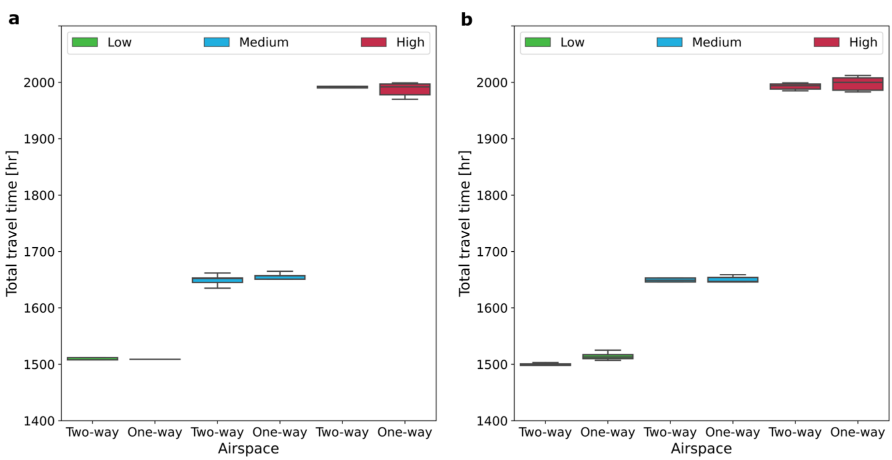

Figure 3.12: The total travel time for the two-way and one-way urban airspace concept for low, medium and high traffic demands. (**a**) Without conflict resolution. (**b**) With conflict resolution.

3.6. DISCUSSION

Traffic culminating from drone-based package delivery has the potential to proliferate the very low altitude urban airspace in high densities and accommodating such traffic will become a challenge. Currently, heavy reliance has been placed on measures, such as 4-D trajectory planning and detect-and-avoid technologies [15]. However, employing the latter methods alone may adversely affect the overall safety of the airspace [84, 88, 90]. What is needed is a concerted effort between the airspace design and the tactical conflict resolution measures. Yet, less is known regarding how the urban airspace can be effectively organised and structured for high-density drone traffic operations. In this current study, we give an example of how the principles of traffic alignment and segmentation can be applied to the heavily-constrained airspace above the existing urban street network, in an effort to facilitate large-scale drone traffic in the constrained very low-altitude airspace.

In this study, we investigated the performance of two concepts: a two-way and one-way urban airspace concept, which were subsequently applied to the street network of Manhattan, New York (encompassing an area of 59.1 km^2) in a comparative simulation experiment. With 60 randomised fast-time simulations that involved over 200,000 drone flights, we identified the one-way airspace concept as having better performance when compared to the two-way concept. The performance of both airspace concepts was evaluated while using a set of key metrics: safety, which measured the total number of conflicts and intrusions; stability, which evaluated the stability of the airspace concept using the Domino Effect Parameter; the throughput, which measured the rate of drone arrivals; the average number of turns per flight in each concept; and, the cumulative travel time.

The safety results that are presented in this study indicate that vertically segmenting traffic with respect to travel direction as well as imposing horizontal structure to the flow of drone traffic in a constrained urban environment is beneficial for airspace safety. The one-way concept demonstrated this. Fundamentally, this increase in safety is associated with segmentation and the reduction of relative velocities between cruising traffic as a result of greater alignment of cruising traffic in each respective altitude layer. These observations are consistent with previous studies on air traffic segmentation and alignment [181, 184].

Even though the total number of intrusions decreased for both concepts when the tactical conflict resolution algorithm was switched on, the total number of conflicts was higher for both concepts. This increase in the total number of conflicts was caused by secondary conflicts or conflict chains due to the scarcity of the airspace, caused by the highly constrained airspace structure, when conflict resolutions take place. Having a constrained airspace limits flexibility for resolution manoeuvres and, therefore, creates secondary conflicts. Similar findings were also reported in the Metropolis airspace design study for two highly structured airspace concepts [183, 184]. In this study, the formation of secondary conflicts was confirmed by positive values in the Domino Effect Parameter, which denoted, at most, one additional conflict per conflict resolution, in all three traffic demand cases for both airspace concepts. Such observations can be compared to on-ground highway traffic, for which the braking of a leading vehicle would cause the follower vehicles to brake without creating any instabilities to the traffic flow. However, if highway traffic demand is extreme, then instability to the flow of traffic can be expected. Therefore, in this current study, the one additional conflict per resolution or a Domino Effect Parameter close to one may not necessarily indicate airspace instability. Future studies should include greater traffic demand estimates to investigate whether the Domino Effect Parameter would increase beyond one.

In terms of efficiency, the rate of arrivals (throughput) was proportional to the traffic demand in both airspace concepts. This was opposite to what was initially hypothesised and, therefore, indicates that the network has not reached its maximum capacity. In particular, future work should investigate the performance of the two airspace concepts for much higher traffic demand levels in order to determine whether the network would become congested and, hence, reach its maximum capacity. Furthermore, the one-way concept consisted of additional altitude bands as compared to the two-way concept, on average. However, both concepts manifested a similar rate of arrivals, which is in contrary to our initial hypothesis. This means that having a higher number of vertical altitude bands to accommodate additional traffic per cardinal direction may not necessarily lead to higher rate of arrivals or throughput.

The average number of turns in a flight is the main difference between the airspace concepts. The two-way concept resulted in, on average, two additional turns per flight-plan, as compared to the one-way concept. This is in contrary to what was initially hypothesised and opposite to the findings that were reported in past on-ground transport street network studies [72, 139]. This difference is a result of the horizontal constraints that are imposed to the traffic flow. When no horizontal structure is imposed to the flow of traffic, the routing algorithm [76], which finds a path from an origin to a given destination with the shortest distance, has many more possible combinations of paths to select. As a result, the chosen shortest-path may be a path with a relatively higher number of turns. However, when horizontal constraints are enforced to achieve one-way directional traffic flow, the possible combinations of shortest-paths to choose from is much lower and, thus, the selected path is one with a relatively lower number of turns.

Note that the routing algorithm causes this difference in the number of turns, and therefore not necessarily an inherent difference between the airspace concepts. In principle, the route optimisation algorithm can also be set up to optimise for minimum number of turns, which is known as the simplest path [22, 200]. On the other hand, as compared to the two-way concept, the one-way concept provides twice as many vertical layers per allowed flight direction to evenly distribute flights along a given street. In the two-way concept, a similar distribution has to be achieved by spreading traffic over different (parallel) streets. This horizontal distribution has the potential to lead to (slightly) more turns, on average, per flight. The higher number of turns in the two-way concepts resulted in more drone flights reducing speed in order to turn safely. This extra number of turns in the two-way concept can also be traced back to the greater number of conflicts and intrusions, where a reduction of speeds at turns may have triggered a proportion of the conflicts and intrusions.

The findings in this study have some limitations. First, our simulations employed a testing region comprising of an orthogonal grid-like street network (i.e., Manhattan street network). Although orthogonal grid-like street networks are prevalent in many parts of the world [29], there still exist seven other types of common street networks [18]. Therefore, we caution extrapolating the findings to non-orthogonal street networks. Second, in our study the investigation of airspace safety was limited to the number of conflicts and intrusions. However, there are more conflict properties worth analysing, such as the location of where conflicts arise and end and, the type of conflicts, for example, the proportion of head-on, side and rear conflicts. Addressing the latter would further enhance our understanding of the observed differences between the two-way and one-way concept. Third, our study neglected meteorological effects such as hyperlocal wind. Depending on the direction and magnitude of the wind, drones could explore such meteorological effects to their advantage and thus allow for lower travel times and higher drone arrivals per minute. Conversely, hyperlocal wind could also concentrate traffic and force drones to fly off course, thereby reducing the overall safety of the airspace. Fourth, to reduce the complexity of our simulations, take-off and landing phases were not considered. The inclusion of these phases may negatively influence the safety results. Fifth, the findings of our study should not be extrapolated to fixed-wing drones, which have different performance characteristics compared to multi-rotor drones. Sixth, the current study focused on airspace designs that remain static over time and one that has uniform traffic distribution patterns. To cope with the paradigm of on-demand delivery services of express packages and fast-food meals, future drone delivery operations will require to operate in a flexible manner. This means that the traffic demand may evolve within a given time while some regions of the airspace will have more traffic than the rest hence, requiring the airspace to dynamically reconfigure [88].

3.7. Conclusions

Drone-based delivery of express parcels and fast-food meals is expected to operate in dense cities in high densities. Such applications may present several societal benefits with respect to air pollution, traffic congestion and, cost-savings to logistics providers. However, the urban airspace is heavily constrained because of existing street networks and its associated landform structures. As a result, accommodating large-scale drone traffic in constrained environments will become a major challenge. To better cope with this, the current study investigates two novel airspace design concepts, namely, the two-way and one-way concept, for the constrained urban environment. Based on the principles of traffic alignment and segmentation, both airspace concepts employed heading-altitude rules to vertically separate cruising traffic with respect to their heading directions. To simulate a constrained environment, the airspace concepts were applied to the street network of Manhattan, New York. A comparison of the performance of the two-way and one-way airspace concepts was conducted using 60 randomised fast-time simulations. Our results show that having vertically segmented altitude layers to accommodate traffic with similar directions and some horizontal constraints imposed to the flow of traffic, in a constrained urban environment, is beneficial for safety.

This study provides interesting avenues for future research. We recommend a follow-up study to examine the properties of traffic conflicts between the two-way and one-way concept. In addition, we encourage further studies to investigate dynamic airspace designs to cope with future on-demand drone-based delivery services of express packages and fast-food meal orders. Furthermore, future studies should examine the effect of hyperlocal winds to how it affects the distribution of traffic and the safety of the airspace. Future research should also consider the take-off and landing phases in the simulations.

4

PROPERTIES OF CONFLICTS AND INTRUSIONS OF CONSTRAINED URBAN AIRSPACE CONFIGURATIONS

The research presented in the previous chapter applied the principles of traffic alignment and segmentation to a constrained urban airspace setting to mitigate conflict probability. In that chapter, two airspace concepts were proposed: two-way and one-way concept, which employed a heading-altitude rule to vertically segment traffic with respect to their travel directions. In addition, the one-way concept also featured horizontal constraints to enforce unidirectional traffic flow. The analysis performed in the previous chapter indicates the one-way concept to be more effective than the two-way concept in terms of safety. To gain a better understanding of the intricate differences between the two-way and one-way concepts, the research in this chapter aims to explore and analyse salient conflict properties. By using fast-time simulation experiments, the different types of conflicts are captured for multiple traffic demand levels. The results suggest that conflicts are largely triggered by flights that climb or descend to their respective altitude layers. These merging conflicts consists of in-trail and crossing conflicts, while the two-way concept also contains head-on conflicts.

A part of the content of this chapter has been published in:

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4.1. INTRODUCTION

Drones have the potential to transform the transportation network of cities by offering time-saving services, such as the delivery of express packages, fast-food meals, vital medical supplies as well as the transport of passengers within urban environments [66, 70, 101, 117]. Over the years, interest for these applications has mainly grown because drone-based delivery is assumed to yield economic, environmental and societal benefits [179]. As a result, many drone delivery companies have been established. One such company is Zipline, which regularly delivers life-saving medicines and vaccines to hospitals in rural areas [1]. Yet, the full potential of drone delivery might only materialise when large-scale drone-based delivery operations is deployed in dense urban areas [50, 51]. However, it is a challenge to safely facilitate high densities of drone traffic in such areas, because the low-altitude urban airspace is highly constrained with physical landform structures and its existing street networks [147].

In order to cope with the future demand for urban drone delivery, a recent study proposed two novel airspace design concepts [53]. In that study, the fundamental principles of traffic segmentation and alignment ([89]) were applied to a constrained urban environment to generate the two-way and one-way airspace concepts in an effort to mitigate conflict probability [53]. For both concepts, a heading-altitude rule was used to vertically segment traffic to different altitude layers with respect to their travel directions. In addition, the one-way concept featured horizontal constraints to ensure unidirectional traffic within a street, while the two-way concept accommodated bidirectional traffic flows. Both concepts were applied to the urban street network of Manhattan, New York city in an attempt to simulate a constrained urban environment. Subsequently, the concepts were compared and evaluated using fast-time simulations for multiple traffic demand scenarios. The study concluded the one-way airspace configuration to be more effective than the two-way concept in terms of safety [53].

The current study extends this research with the goal of understanding the types of conflicts and intrusions generated in the two-way and one-way airspace concepts. Characterising the statistics of merging, in-trail, crossing and head-on conflicts could help guide future work in urban airspace design and, conflict detection and resolution research. Similar research has been done, albeit for air traffic management [114] and road traffic [210]. In this study, we use fast-time simulations to compare the performance of the two concepts for multiple traffic demand levels with respect to the number of conflicts, intrusions, and their constitute properties.

The remainder of this chapter is organised as follows. Section 4.2 describes the two-way and one-way urban airspace design concepts. Section 4.3 outlines the experimental set-up and Section 4.4 presents the results of our experiments. We then discuss the main finding in Section 4.5 and provide some concluding remarks in Section 4.6.

4.2. URBAN AIRSPACE CONCEPTS

To simulate a constrained urban environment, both concepts are applied to an existing urban street network. As a result, the drone flight-routes conform to the urban street network, similar to road vehicles, albeit also utilising the third dimension to separate converging traffic flows. In both concepts, traffic is organised into different altitude layers corresponding to the four cardinal directions: north, east, south and west. This means that the two-way and one-way concepts consist of multiple stacks of layers that span the altitudes of 75 ft to 1050 ft which accommodate traffic with respect to their travel directions [53]. In addition to this vertical distribution of traffic, the one-way concept contains horizontal constraints to create unidirectional flow of traffic, similar to how road traffic can be organised by one-way streets [38, 71, 176].

4.2.1. PRELIMINARY OBSERVATIONS

TURNING FLIGHTS

In our initial experiments, we defined a constant drone speed of 10.3 m/s and a maximum bank angle of 35°. The preliminary experiments showed a strong interplay between the turn radii at intersections of the street network and the drones' performance [53]. We observed that the drones would overshoot their original flight-path at intersections, especially when flying at a constant speed. Depending on the distance between the drone and the intersection, our initial experiments indicated the need for drones to decelerate in order to safely execute turns.

THROUGH AND TURN ALTITUDE LAYERS

To accommodate the turning traffic, turn altitude layers are incorporated in the two-way and one-way concepts (see Figure 4.1). As a result, the turn-layers separate turning traffic from through traffic and thus reduces the likelihood of disruption to the flow of through traffic. A similar design scheme is used in road design to differentiate slow and fast traffic [71]. Note that through traffic is defined as traffic that passes at least one intersection, while turn traffic is identified by traffic that requires to turn at an intersection.

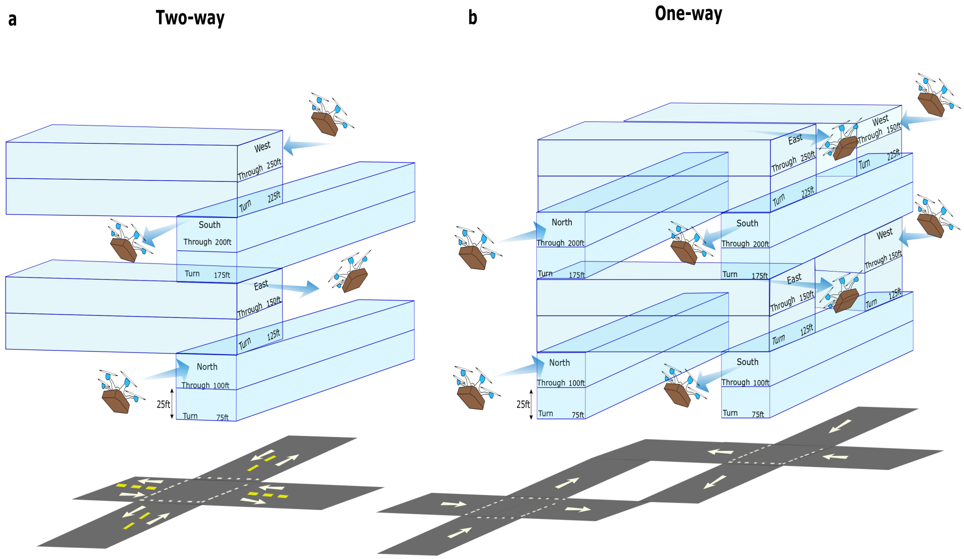

Figure 4.1: Schematic view of one set of altitude layers for the two urban airspace design configurations, where each altitude layer corresponds to the respective travel direction. Note that the airspace configurations consist of through-layers and turn-layers. Through-layers are used by through traffic which passes through at least one intersection. While the turn-layers are utilised by transitory flights, that is, flights that need to perform turns at the respective intersections. **(a)** Two-way layer concept of one set of altitude layers. **(b)** One-way layer concept depicting.

4.2.2. Design concepts

In this study, the two-way and one-way airspace design concepts have 40 altitude layers that consist of 20 turn-layers and 20 through-layers (see illustrations in Chapter 3). Each layer has a vertical separation of 25 ft. As an illustrative description, in Figure 4.1, we present a schematic 3D illustration of one set altitude layers that fit into the altitude range 75 to 250 ft for the airspace concepts. Therefore, to get the complete set of 40 altitude layers, the set of eight altitude layers is repeated five times until 1050 ft [53]. This section summarises the two airspace concepts.

Two-way

The traffic in the two-way airspace concept is assigned with respect to a heading range of 90°. This division of traffic with flight headings, ψ, creates four quadrants: northbound layers, which are defined within $315° < \psi \leq 045°$; eastbound layer, for $045° < \psi \leq 135°$; southbound layers, within $135° < \psi \leq 225°$; and flight headings $225° < \psi \leq 315°$ to westbound layers. The two-way concept contains multiple altitude layers that range from 75 ft to 1050 ft that encapsulate a total of 40 altitude layers. These layers are equally segmented to include 20 through and 20 turn layers. Moreover, 10 altitude layers are allocated to north, east, south and westbound directions. Using the heading-altitude rule of Equation (4.1), we allocate short distance flights to the lower altitudes and longer distance flights to higher portions of the altitude.

$$h_{TW,i} = h_{min} + \zeta \left[\left[\frac{d_i - d_{min}}{d_{max} - d_{min}} \kappa \right] \beta + \left[\frac{\psi_i}{\alpha} \right] \right] \tag{4.1}$$

Note that the above heading-altitude rule (Equation 4.1) is a function of the flight heading ψ_i, its shortest path distance, d_i and the minimum and maximum threshold distances (d_{min} and d_{max} which is defined between 1 km and 10 km, respectively). The remaining constants include the heading range per flight level, α, which is equal to 90°; the minimum altitude of the through-layer, h_{min} (i.e., 100 ft); β, which is equal to 4 (i.e., 360°/ α); κ as 5 and; the vertical distance (ζ) between through-through-layers is equal to 50 ft.

4

ONE-WAY

The one-way concept consist of 40 altitude layers, which contains of 20 through and 20 turn traffic layers. Here, horizontal constraints are imposed to the direction of travel in order to promote one-way traffic flow. This generates unidirectional traffic flow over a single street. As a result, a street can either accommodate north, east, south, or westbound traffic. Note that the prohibition of opposite flow of traffic in a single street enables for an additional set of layers. Therefore, compared to the two-way concept that has 10 altitude layers per cardinal direction, the one-way concept has 20 altitude layers per cardinal direction. Similar to the two-way concept, the layering in the one-way design is organised with respect to the heading range of 90° with flight headings ψ: 315° $< \psi \leq$ 045°, for northbound layers; 045° $< \psi \leq$ 135°, for eastbound; 135° $< \psi \leq$ 225°, southbound; 225° $< \psi \leq$ 315°, to westbound layers. To compute the respective cruising altitudes ($h_{OW,i}$), we employ the following heading-altitude rule:

$$h_{OW,i} = h_{min} + \frac{h_{max} - h_{min}}{d_{max} - d_{min}} (d_i - d_{min}) \tag{4.2}$$

Equation 4.2 ensures that short distance flights is assigned to the lower portions of the airspace while long distance flights are allocated to higher altitudes. In addition to the above heading-altitude rule, we also use a simple heuristic, as described by Algorithm 2, to align flight to their altitudes with respect to their flight heading. Note that ζ denotes the vertical distance (25 ft) between layers.

Algorithm 2: Heuristic to align flight altitudes to their travel direction.

if $315° < \psi \leq 045°$ or $135° < \psi \leq 225°$ **then**
  $h_{OW,i} = h_{OW,i}$
else
  if $045° < \psi \leq 135°$ or $225° < \psi \leq 315°$ **then**
    $h_{OW,i} = h_{OW,i} + \zeta$
  end if
end if

4.3. EXPERIMENTAL DESIGN

A set of fast-time simulation experiments were performed to compare the safety of the two-way and one-way concepts. This section describes the experiment conducted in this study.

4.3.1. EXPERIMENTAL METHODS

SIMULATION PLATFORM

In this study, fast-time simulations are conducted using the open-source Air Traffic Management simulator BlueSky [85]. The simulation platform's autopilot module and its drone model database was expanded to feature characteristics of urban drone-based delivery. In this work, we employ the DJI Matrice 600 Pro hexacopter drone model since it is a popular delivery prototype. The characteristics of this drone model is presented in Table 4.1.

Table 4.1: Performance data for DJI Matrice 600 Pro used in the simulations of this study.

Parameter	**DJI Matrice 600 Pro**
Speed [m/s]	5-10.3
Vertical speed [m/s]	-5-5
Mass [kg]	15
Maximum bank angle [°]	35
Acceleration/deceleration [m/s^2]	3.5

EXPERIMENTAL AREA

We examine the performance of the two-way and one-way concept by overlaying them over the urban street network of Manhattan, New York City (Figure 4.2). Manhattan represents an orthogonal or grid-like network which is ideal for this study [53]. The red shaded circles in Figure 4.2 represent three drone hubs or depots where drones depart to deliver packages to customers.

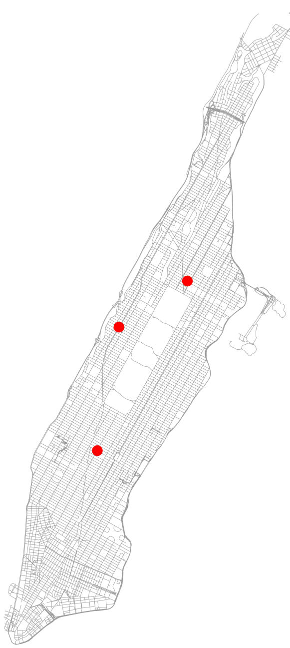

Figure 4.2: Urban street network of Manhattan, New York City, which consists of an area of approximately 59.1 km^2. The three circles shaded in red represent the location of the drone depots.

CONFLICT DETECTION AND RESOLUTION

The two-way and one-way concepts relied on a state-based conflict detection method and a basic 1-D speed control algorithm (tactical conflict resolution) to identify and resolve potential separation violations in a pair-wise manner [53]. In this study, we adopted a horizontal and vertical separation requirement of 82 ft and 25 ft, respectively. These requirements were chosen based on its suitability in initial test simulations [53].

AIRSPACE CONCEPT IMPLEMENTATION

The street network of Manhattan (4091 nodes and 9453 edges) was obtained from OpenStreetMap [28]. Subsequently, an undirected and directed graph was generated for the two-way and one-way concept, respectively. The directed graph ensures the direction of the streets in the one-way concept to be unidirectional.

While the undirected graph ensures the streets in the two-way concept to be bidirectional.

In both concepts, we used three drone depots where drones depart to randomly assigned destinations by flying their respective shortest path [53]. To account for the drones' limited range, a minimum and maximum distance of 1 km and 10 km was defined. Based on the generated shortest paths, consisting of a set of latitude and longitudinal coordinates, the flight headings and the location of turns were computed for every street along its respective shortest path. Similarly, the cruise altitudes were found using the heading-altitude rules described in Section 4.2. Then using the turn locations, we determined the transition altitudes for the respective flights.

4.3.2. INDEPENDENT VARIABLES

For this experiment, we used three independent variables, namely; the urban airspace concepts, which consist of the two-way and one-way concept; the airborne separation conditions, i.e., when conflict resolution is enabled and disabled; and the traffic demand level, which consist of low, medium and high densities of traffic. Note that the three traffic demand scenarios are based on a potential scenario of fast-food meal delivery via a fleet of autonomous drones (see Chapter 2). The traffic demand levels used in this study is presented in Table 4.2.

Table 4.2: Traffic density characteristics of the three demand scenarios for the simulation area of Manhattan, New York City, network consisting of an area of 59.1 km^2.

	Low	**Medium**	**High**
Traffic density (drones/km^2)	55	61	73
Inflow rate (drones/min)	54	60	72
Hourly demand (drones/hr)	3240	3600	4320
Demand per depot (drones/depot)	1080	1200	1440

The simulations here contain 12 experimental conditions, which consist of two airspace concepts, two conditions of conflict resolution (i.e., conflict resolution on and off) and three traffic demand levels. To improve the accuracy of the experiments, three repetitions were performed for each experimental condition. Furthermore, in each simulation run, uniformly random destinations between 1 km and 10 km were used in order to have different drone trajectories.

4.3.3. DEPENDENT MEASURES

In this study, we analyse the dependent measure of safety and its constitute properties for the two-way and one-way urban airspace concept.

SAFETY

The safety of the two urban airspace concepts is defined by the number of conflicts and intrusions. An intrusion is defined when the vertical and horizontal separation requirements have been violated. A conflict is denoted as a predicted loss of separation or an intrusion within the prescribed look-ahead time of 10 *s*. The 10 *s* look-ahead time was selected based on trial experiments which demonstrated an acceptable ratio between the number of false conflict detections and the number of actual conflict detections. Note that, in this study, a safer airspace concept is reflected by a lower number of conflicts and intrusions. Therefore, we measured the total number of pairwise conflicts and intrusions for the two-way and one-way concept.

To better understand the intricate differences between the airspace concepts, in terms of safety, we assessed the total number of pairwise conflicts and intrusions for each conflict and intrusion type, which includes in-trail; head-on; crossing conflicts and intrusions; for both level and non-level flights (i.e., merging flights). Next, for each conflict type we capture the Intrusion Prevention Rate (IPR) using Equation 4.3. The IPR indicates the proportion of intrusions that is successfully prevented and thus it demonstrates the effectiveness of the conflict resolution algorithm.

$$IPR = \frac{C_{total} - I_{total}}{C_{total}} \tag{4.3}$$

4.4. RESULTS

The effect of the independent variables on safety is illustrated using box-and-whisker plots and stacked bar plots. The box-and-whisker plot depict the median line; the interquartile range (IQR), which is marked by the boundary of the box; the minimum and maximum distribution of the data, which is denoted by the whiskers; and the outliers, which is represented by points greater than $\pm 1.5\times$ IQR. Furthermore, the different categories of conflicts and intrusions is presented using stacked bar plots.

4.4.1. TOTAL NUMBER OF CONFLICTS AND INTRUSIONS

Figure 4.3 and 4.4 show the total number of pairwise conflicts and intrusions for the two-way and one-way concept for low, medium and high traffic demand levels. It is worth nothing that a pairwise conflict and intrusion is counted only once, independent of its duration, during the simulation, while a recurring conflict and intrusion is recounted.

Across both concepts, the total number of conflicts and intrusions increased with traffic demand (Figure 4.3 and 4.4). The figures indicate the one-way concept has lower number of conflicts and intrusions compared to the two-way concept. Figure 4.3 and 4.4 also demonstrate the effect of tactical conflict resolution for the two-way and one-way concept. When conflict resolution is disabled, the one-way concept has better intrinsic safety and thus it is able to reduce the occurrence of conflicts when compared to the two-way concept. Furthermore, both concepts showed a marked decrease in the number of intrusions when conflict resolution was enabled. On the other hand, the number of conflicts displayed a reverse effect. In both concepts, the number of conflicts increased when conflict resolution was switched on. This behaviour could be a consequence of the heavily constrained urban airspace, which limits the flexibility for resolution manoeuvres thereby forming conflict chains.

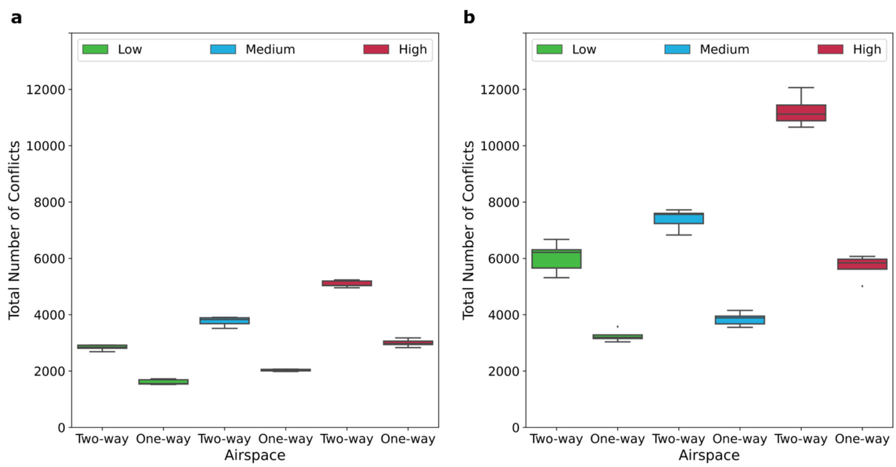

Figure 4.3: The total number of pairwise conflicts for the two-way and one-way urban airspace concept for low, medium and high traffic demands. (**a**) Without conflict resolution. (**b**) With conflict resolution.

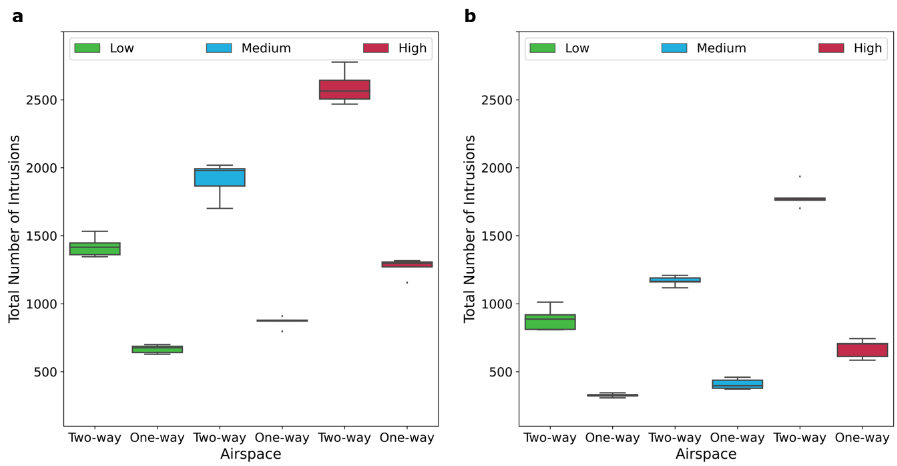

Figure 4.4: The total number of pairwise intrusions for the two-way and one-way urban airspace concept for low, medium and high traffic demands. (**a**) Without conflict resolution. (**b**) With conflict resolution.

4

4.4.2. NATURE OF CONFLICTS AND INTRUSIONS

Figure 4.5 and 4.6 present the different types of conflicts and intrusions for the two-way and one-way concepts. The bar graphs show that conflicts and intrusions are primarily generated by flights that are climbing or descending (i.e., merging flights) to their respective altitude layers. We see that the majority of conflicts is triggered by in-trail and crossing flights. Notably, the charts highlight a significant difference between the two-way and one-way concept. The charts show a large proportion of head-on conflicts in the two-way concept, while head-on conflicts are not possible in the one-way concept, due to the fact that opposite traffic flows are laterally separated by the urban street network. Moreover, most head-on conflicts triggered in the two-way appear to be short-term since they are largely resolved, as demonstrated in Figure 4.6.

4.4.3. INTRUSION PREVENTION RATES FOR DIFFERENT TYPES OF CONFLICTS

To gauge the ability of the airspace concept to solve conflicts without causing intrusions, we examined the IPR composition of in-trail, crossing and head-on conflicts for both merging and non-merging flights (see Figure 4.7). Even though the absolute number of conflicts and intrusions increased with traffic demand, the plots illustrate the IPR to be independent with traffic demand. And, despite there being some variability in the IPR between the two-way and one-way concepts, no significant trend can be deduced from the plots.

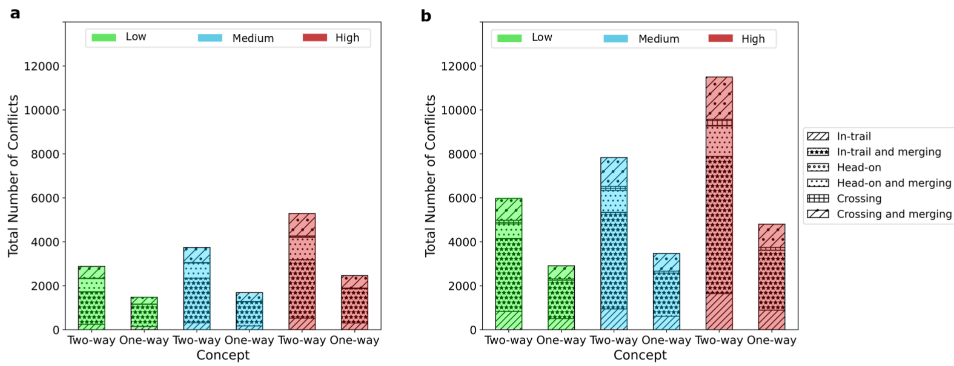

Figure 4.5: The total number of pairwise conflicts and their associated type for the two-way and one-way urban airspace concept for low, medium and high traffic demands. (**a**) Without conflict resolution. (**b**) With conflict resolution. The results show that a substantial number of conflicts is generated by merging flights. The results also underscores the presence of head-on conflicts in the two-way concept.

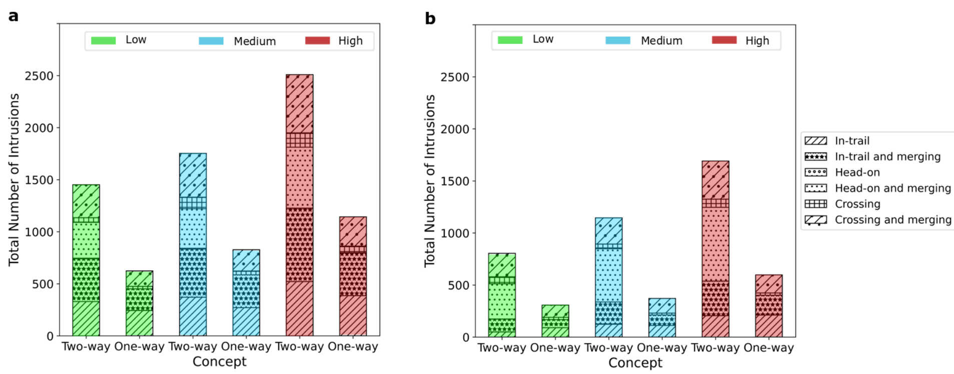

Figure 4.6: The total number of pairwise intrusions and their associated type for the two-way and one-way urban airspace concept for low, medium and high traffic demands. (**a**) Without conflict resolution. (**b**) With conflict resolution.

Notably, Figure 4.7a depicts a non-zero IPR for all types of conflicts in both concepts with conflict resolution disabled. These conflicts are known as *false conflicts* since they are largely resolved without any intervention from the tactical conflict resolution algorithm. Here, false conflicts are probably triggered by the conflict detection algorithm which is a state-based method that linearly extrapolates the drones' trajectories in order to predict conflicts [90]. As a result of this straight-line extrapolation method, it is likely that climbing and descending flights, as well as turning flights, generate conflicts when they are in their projected flights paths at a given moment of time.

We observed an apparent increase in the prevention of intrusions with the tactical conflict resolution enabled. This is evidently reflected with high IPR values of nearly 90 percent for in-trail conflicts (Figure 4.7b). Similarly, when conflict resolution is switched on, no noticeable trend can be seen between the two-way and one-way concept. Therefore, the absolute number of intrusions is a better indicator when comparing the performance of the airspace concepts. Nevertheless, the IPR gives an indication of the ability of the conflict resolution algorithm in avoiding intrusions for the different types of conflicts. Here, we observe that speed-based conflict resolution algorithm is less effective in preventing head-on and crossing intrusions.

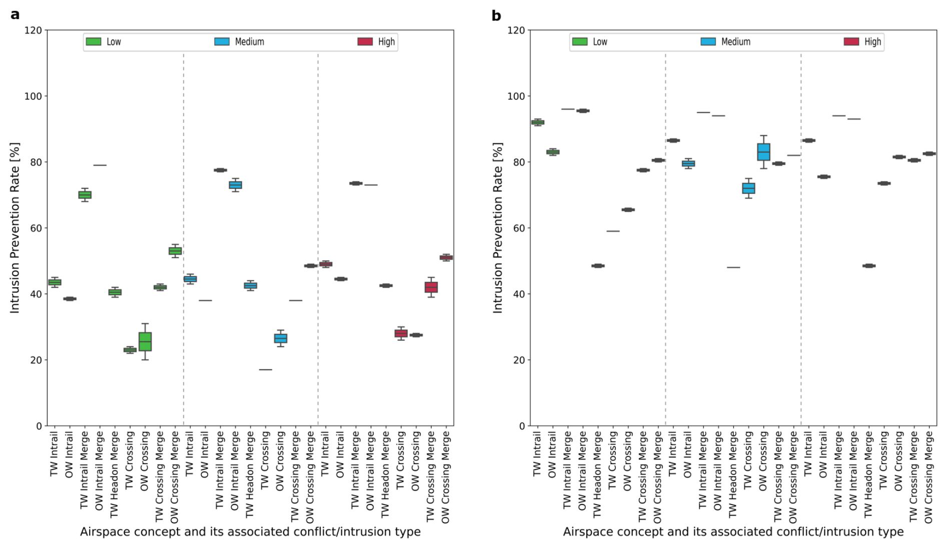

Figure 4.7: The Intrusion Prevention Rates for the different types of conflicts in the two-way (TW) and one-way (OW) urban airspace concept for low, medium and high traffic demands. (**a**) Without conflict resolution. (**b**) With conflict resolution.

4.4.4. SPATIAL DISTRIBUTION OF CONFLICTS

Figure 4.8 and 4.9 exhibit the location of instantaneous conflicts in both concepts without and with tactical conflict resolution. The left graph in Figure 4.8 and 4.9 displays the conflict locations for the two-way concept, while the right plot depicts the location of conflicts for the one-way concept. The plots suggest that some conflicts appear to be repeating with time as illustrated by the long continuous similarly coloured points. These repeating continuous conflicts, however, appear to reduce when conflict resolution is enabled (see Figure 4.9).

Although a uniform traffic distribution is assumed, the maps indicate that some regions of the network have more conflicts than the rest. This effect may be explained by the network's high betweenness centrality of nodes which means that some nodes have higher number of shortest pathways passing through and thus it is used more often [106]. Note that this is a property of the employed urban street network.

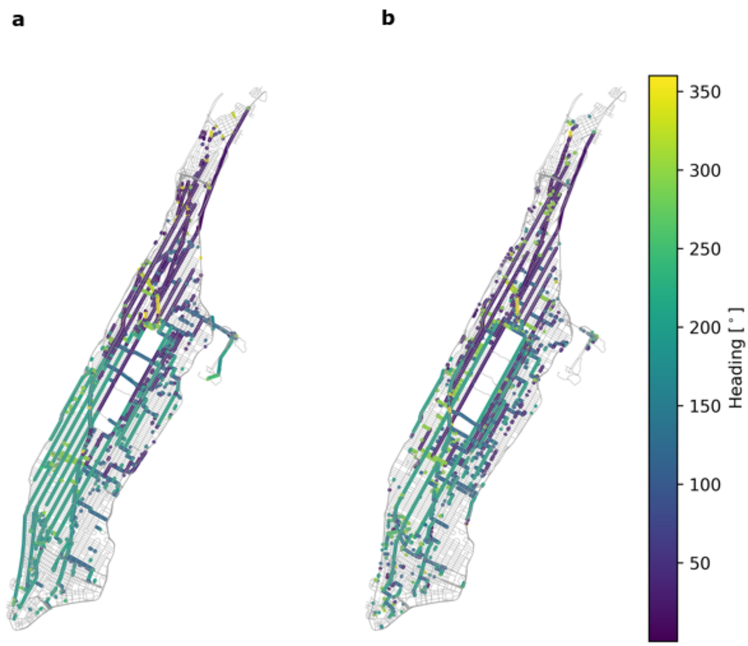

Figure 4.8: Geographical locations of instantaneous conflicts for low, medium and high traffic demand levels without conflict resolution. **a**, Instantaneous pairwise conflict locations in the two-way concept. **b**, Instantaneous pairwise conflict locations in the one-way concept.

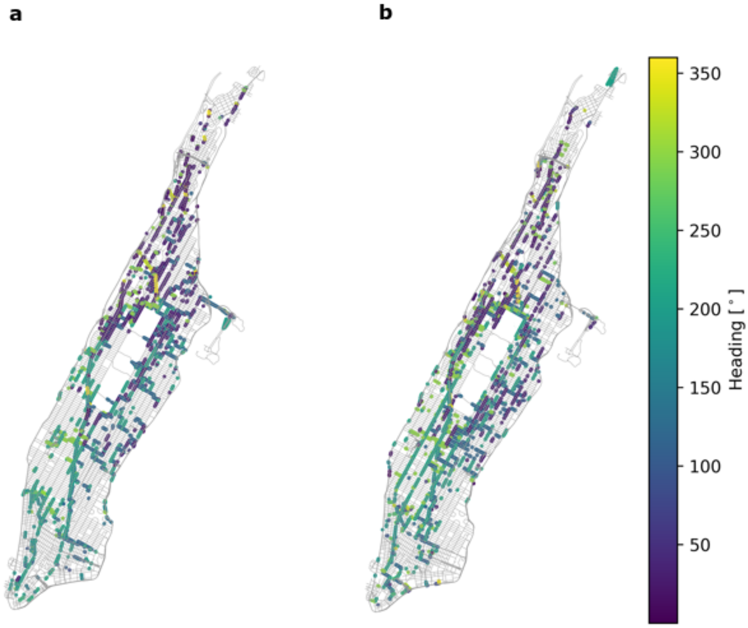

Figure 4.9: Geographical locations of instantaneous conflicts for low, medium and high traffic demand levels with conflict resolution enabled. **a**, Instantaneous pairwise conflict locations in the two-way concept. **b**, Instantaneous pairwise conflict locations in the one-way concept.

4.5. DISCUSSION

Delivery drones are expected to operate in the low altitude airspace at high traffic densities. This portion of the airspace is heavily constrained with physical structures and existing urban street networks and therefore, to safely facilitate large-scale drone traffic remains an enormous challenge. A previous study has proposed solutions that rely mainly on strategic and tactical de-confliction measures [15]. However, what might be needed is a combination of airspace structure as well as strategic and tactical de-confliction for the safe accommodation of large-scale drone traffic in constrained environments. By employing the principles of traffic alignment and segmentation, a recent study proposed and evaluated the implementation of two novel airspace designs, namely, the two-way and one-way configurations [53]. In that study it was revealed that the one-way airspace configuration is more effective than the two-way concept in terms of safety [53]. To increase our understanding of the intricate differences between the two-way and one-way airspace designs, the current study investigates the types of the conflicts and intrusions.

In this research, we apply the two-way and one-way airspace concepts to the urban street network of Manhattan, New York (which encapsulates an area of 59.1 km^2) to simulate a constrained environment. Using randomised fast-time simulations, we examined the safety of both airspace designs. Here, we compared safety in terms of the total number of conflicts and losses of separation. To better understand the difference in safety, we measured four types of conflicts and intrusions. The results suggest that conflicts are predominately triggered when drones merge to their respective altitude layers. These merging conflicts largely occur because of two main factors. First being the altitude-heading rule which assigns flights to different altitude layers based on respective travel directions. Second, is the implementation of the conflict detection and resolution algorithm which does not have information about merging flights and thus it is not optimised for reducing merging conflicts. Our results indicate that the two-way concept contains a higher number of in-trail and crossing conflicts and intrusions than the one-way concept. Importantly, the merging conflicts in the two-way concept also largely consisted of head-on conflicts when compared to the one-way concept, which did not experience any head-on conflicts. This disparity could be explained by the structure of one-way airspace configuration for which opposite traffic flows are assumed to be laterally separated by the urban street network.

Our study shows that the one-way concept has fewer conflicts and intrusions than the two-way concept. The types of conflicts in the one-way concept consist of in-trail and crossing conflicts, while the two-way concepts consist of in-trail, crossing and head-on conflict types. The higher level of safety in the one-way concept is caused by the combination of a higher number of vertically segmented altitude layers of traffic and the imposed horizontal structure on the flow of traffic [53]. This imposed structure in the one-way concept circumvents head-on conflicts and intrusions and thus it is the main underlying difference between the two-way concept. Fundamentally, these observations can be explained by the principles of segmentation and traffic alignment which reduces the relative velocities between cruising traffic [53].

In both concepts, conflicts and intrusions are generally caused by flights that are either climbing or descending to their respective altitude layers. These merge conflicts were expected since no measures were in-place to mitigate their likelihood. In road traffic, merge conflicts represent a large proportion of highway collisions [210]. Merge conflicts are commonly caused by insufficient gaps in the traffic flow due to high traffic density [109]. Therefore, as traffic demand increases, the amount of free airspace reduces for merging flights and thereby causing a higher number of conflicts. The fewer number of intrusions (relative to the number of conflicts) further justify that the majority of these conflicts are caused by transitory flights. This means that most of the merge conflicts would never occur since the drones will not be on the same altitude during the predicted conflict. One potential solution to this challenge could be to implement a predictive airborne separation assurance system [86].

In addition to the merging flights that trigger conflicts, a majority of the cohort comprised of in-trail and crossing conflicts. Even though the probability of crossing conflicts is largely reduced due to the structure of the airspace, the relatively shorter distances of street edges in some parts of the network and the high density of traffic imply that merging flights have limited time and space to climb or descend to their respective layers. An example solution to circumvent this type of conflict could be to implement a metering strategy or to impose variable speed limits [110].

Similarly, the ineffectiveness of the speed-based conflict resolution measure to prevent the onset of head-on and crossing conflicts, as depicted by the relatively lower intrusion prevention rates for this particular cohort, might be causing a cascading-effect and thus triggering the emergence of additional conflicts and intrusions. This ineffectiveness of the speed-based algorithm is, however, expected as it is only limited to speed reductions. In our study, we only employ the speed-based conflict resolution method to compare the airspace concepts. In light of this, future studies should also investigate the use of direction change to prevent these types of conflicts.

Using conflict maps, we captured the location of conflicts in both concepts. The spatial distribution of conflicts indicates that a large portion of the conflicts probably occurs at intersections due to flights reducing their speed to perform turns. Such conflicts may also exhibit continuous repetition of the conflict over time. The conflict maps also locate geographical hotspot regions in both concepts thus indicating that some street edges are utilised more than the rest. This spatial clustering of conflicts to specific swathes of the network could lead to local congestion and thus more conflicts. This effect, however, may be caused by a particular property of the urban street network and not necessarily the structure of airspace concepts. A recent study demonstrated that some street networks exhibit high betweenness centrality, which means that some intersections experience a disproportionately higher number of traffic flow, due to a larger number of shortest paths going through the intersections [106]. In practice such localised concentrations of traffic could be mitigated by (strategic) flow control, and individual routing strategies. Future research should therefore investigate whether redistributing traffic flows to under-utilised portions of the network as a potential means to mitigate the probability of conflicts.

Our results are subject to some limitations. First, our airspace design concepts were applied to a test region that featured an orthogonal street network. Even though orthogonal street networks are largely represented in most cities [29], there still exist seven other types of street networks [18]. Recent studies have identified a growth in non-orthogonal street networks, which are inflexible and less connected street networks [18, 19]. These non-grid networks have different properties, such as high fraction of dead-ends and high dendricity (tree-like networks). For road traffic, less connected urban street networks are associated with increased vehicle travel kilometres, energy use and emissions [18]. Hence, validating the airspace configurations for non-orthogonal street network topologies, such as the ones found in cities like Amsterdam or Paris, could be an interesting research direction. Second, our research was limited to the number of conflicts and intrusions, its classification and the locations of conflicts. Road traffic studies have also examined temporal and spatial proximity measures, such as time and distance to conflicts, to better understand the severity of conflicts [212]. Therefore, it is worth analysing similar measures for the two-way and one-way airspace concepts. Third, the airspace configurations remain static with time and assume uniform distribution of traffic. However, to cope with the paradigm of on-demand transport, a dynamic airspace is required, that is, one that adapts to temporal variations in patterns of traffic demand [88]. Nevertheless, future research should investigate dynamic airspace designs for on-demand transport of goods and services.

4.6. CONCLUSIONS

This study investigated the properties of conflicts and intrusions of the two-way and one-way urban airspace design concepts for large-scale drone delivery traffic. Both concepts were applied to the street network of Manhattan, New York, in an attempt to simulate one example of a highly constrained urban environment. Using fast-time simulations, we compared the concepts with respect to the total number of pairwise conflicts and intrusions. Our results show that the one-way concept has fewer conflicts and intrusions thus indicating that vertical segmentation of traffic with respect to flight headings as well as horizontal constraints imposed on the flow of traffic is beneficial for the safety of the urban airspace. For both concepts, we observed that conflicts are predominately triggered by flights that required to climb or descend to their respective altitude layers. The majority of these merging conflicts are composed of in-trail and crossing conflicts in both concepts. In addition to these conflict types, the merging conflicts in the two-way concept also consisted of head-on conflicts. This disparity could be explained by the structure of the one-way concept for which opposite traffic flows are assumed to be laterally separated by the urban street network and thus reducing the emergence of head-on conflicts. Future studies should develop strategies to mitigate the likelihood of merge conflicts, possibly by extrapolating research from road-traffic design.

5

INVESTIGATION OF MERGE ASSIST POLICIES TO IMPROVE SAFETY IN A CONSTRAINED URBAN AIRSPACE

In the previous chapter we showed that conflicts were largely triggered during the merging phase. Therefore, in this chapter, we aim to reduce the occurrence of merging conflicts and intrusions by using a delay-based and speed-based merge-assisting strategy that is broadly used in ground-based transport. We apply the merge assistance strategies in the one-way airspace design and perform simulations for three traffic densities for the experiment area of Manhattan, New York. The results indicate, at most, a 9-16 percent decrease in the total number of intrusions with the use of merge assistance. By investigating mesoscopic features of the urban street network, the data suggest that the relatively low efficacy of the merge strategies is mainly caused by insufficient space for safe manoeuvrability and the inability for the strategies to fully respond and thus resolve conflicts on short-distance streets.

The content of this chapter has been published in:

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5.1. Introduction

Advanced air mobility concepts, such as autonomous drones could play an essential role in future express package delivery missions, for example medical and meal delivery in urban areas [43, 63, 69, 122, 168]. The large-scale adoption of drones for urban delivery missions could potentially help reduce traffic congestion and thus decrease total anthropogenic CO_2 emissions in cities [142, 179]. In contrast to traditional and contemporary transport modes, such as vans and bikes, drones appear to be flexible and cost effective; moreover, they are easily scalable and comparatively less challenging to automate than road vehicles [51].Yet, the radical changes promised by autonomous delivery drones may only begin to have profound and extended effects on society and its urban environment when deployed in large-scale. However, before widespread adoption of delivery drones unfolds in cities, there are many challenges to overcome. As urban environments are densely populated with dynamic and static obstacles ([147]), operating high densities of drone-based deliveries in a confined space presents a safety hazard to urban occupants [203]. Therefore, this raises the question of how to safely accommodate high-density drone traffic in a constrained urban environment. One logical step forward is to have a suitable urban airspace structure as a means to support these flying robots in dense cities [51].

Previous studies have addressed some of these concerns by proposing corridors and sky-lanes ([98, 192]), and even advocating conceptual rules-of-the-road, such as giving priority for traffic on the right at intersections as a potential means to safely navigate through urban areas ([92]). Some have suggested single altitude lane-based approaches that primarily investigated trajectory scheduling algorithms in a way to tackle strategic conflict management [162, 163]. While others have focused on conceptual design studies into the use of airway routes over buildings, railways and roads for the city of Singapore [121, 132], a majority of the work has been centred towards policy-based studies for Europe's advanced air mobility traffic management program, U-Space [6, 15, 35, 127]. However, the common thread in these studies is that they are mainly limited to very low traffic densities of drones or even single drone flight operations.

In contrast, quite a large number of studies have been conducted for autonomous flying vehicles operating in unconstrained airspace. The Metropolis project demonstrated that vertical segmentation of cruising traffic according to heading directions leads to favourable levels of safety [183, 184]. In a follow-up study, it was revealed that two principles were primarily associated with lowering the conflict probability, namely, the segmentation of traffic into separate parts of airspace (e.g., geofenced areas, layers of airspace) and the reduction of relative velocities by alignment of traffic within the same airspace segment [88, 89].

The current study is part of a project that aims to apply the findings of the Metropolis project to constrained airspace, where vehicles are restricted to flying along the streets. Many of the challenges faced with large-scale drone operations in highly constrained environments are also present in road transportation [38, 71], especially in automated road vehicles [79, 198]. Because of this, a previous study, which is also part of the current project, combined the Metropolis research of unconstrained urban airspace with principles of road traffic engineering, to propose an implementation of a two-way and one-way airspace configuration [53]. The one-way concept featured horizontal constraints to promote unidirectional traffic within a street, while the two-way concept did not include horizontal constraints and thus allowed bidirectional flows of traffic. Both concepts feature transition altitudes to accommodate turning traffic that requires a deceleration to perform turns at intersections. By separating slower turning traffic from the main flow, these transition altitudes aim to mitigate any interruptions to the flow of through-traffic. However, in a follow-up study, it was shown that despite the presence of transition altitudes, the layered airspace structure generated a large number of merging type conflicts when flights transition between layers for a turn [52]. The current study aims to manage and mitigate the occurrence of merging conflicts through the use of merge assist strategies.

By extrapolating work done in highway merging traffic research ([71, 74, 109, 110, 158]), we investigate the use of a delay-based and speed-based merge assist framework for a large-scale drone traffic simulation study. Using fast-time simulations, we test these merge assist policies for low, medium and high traffic densities with respect to the total number of conflicts, intrusions and their constitute properties. Our study not only investigates the macroscopic properties of the network, but it also examines specific hotspot regions of the network, which features many individual drones interacting in a confined space by following a set of rules, and thus we uncover key mesoscopic properties of the urban network.

In this work, we perform our research based on the context of emerging drone delivery missions, which have the potential to generate high-density traffic scenarios in constrained urban spaces [50]. Therefore, we use this scenario to evaluate the airspace design and the associated merging-assist frameworks with high traffic densities. We are aware that drone delivery is just one potential cohort of users of the urban airspace. Besides that, other advanced air mobility concepts, such as flying taxis ([180]) may also exhibit high traffic densities in a constrained urban airspace [189]. Therefore, the goal of this research is to understand how individual drones interact with each other in a given confined environment and how specific operating rules might trigger undesired emergent behaviour with high traffic densities.

The remainder of this chapter is structured, as follows: Section 5.2 outlines the background material of this study. In Section 5.3, we present the methodology of our study. In particular, Section 5.3.2 describes the merge assistance framework and Section 5.4 gives details about the simulation environment and its set-up. Section 5.5 presents the results of our experiments. The main findings of our study are then discussed in Section 5.6. Finally, Section 5.7 summarises the main conclusions of this study.

5.2. BACKGROUND

In this section, we summarise relevant background material. We start with a brief description of important airspace safety metrics. Then, we discuss how traffic segmentation and alignment help achieve intrinsic safety by preventing the onset of conflicts. Thereafter, we discuss the one-way airspace concept for high-density drone traffic operations and its associated emergent behaviour when applied to a constrained urban environment.

5.2.1. CONFLICTS AND INTRUSIONS

The number of pairwise conflicts and intrusions are metrics to describe the safety of an airspace. Here, an intrusion, or a loss of separation, occurs when the horizontal and vertical separation margins are simultaneously violated. A conflict is defined when the horizontal and vertical separation distances between drones is predicted to be violated within a prescribed 'look-ahead' time. Therefore, a conflict can be viewed as an anticipated intrusion.

5.2.2. APPLICATION OF TRAFFIC SEGMENTATION AND ALIGNMENT

Previous studies have extensively investigated the effect of traffic segmentation and alignment as a potential means to increasing the intrinsic safety of the airspace [88, 89, 181]. Here, we describe traffic segmentation and alignment using the mathematical expression represented by Equation 5.1.

$$CR_{global} = \frac{1}{2}N(N-1)p_2 \tag{5.1}$$

In Equation 5.1, the global conflict rate (CR), or probability of conflict, is related to two parameters. The parameter N indicates the number of vehicles, or drones, in the observed area. Parameter p_2 denotes the probability that any two vehicles in the observed area meet each other, which is dependent on the structure of the routes and airspace. By examining Equation 5.1, it can be seen that for a given volume of airspace, increasing N causes a quadratic increase in CR while increasing p_2 causes a linear increase in CR.

The conflict probability can therefore be mitigated by effectively reducing N and p_2 [88, 89, 181]. A reduction of N can be achieved by the segmentation of traffic, which effectively decreases the likelihood of any possible number of combinations of vehicles that can meet each other within the given airspace. The parameter p_2 has been shown to be composed of factors such as the separation margin and look-ahead time, but also the degree of alignment of trajectories, which can be achieved by reducing the relative speeds between two vehicles in the observed airspace [89].

5.2.3. CHALLENGES OF CONSTRAINED URBAN ENVIRONMENTS

In previous research, the principles of segmentation and alignment were applied to an unconstrained or free airspace [183, 184]. In contrast, drone-based delivery traffic is expected to utilise a highly constrained urban environment that harbours a large presence of dynamic and static obstacles as well as temporary and permanent no-fly-zones [147]. To an extent it shares these operational conditions with autonomous cars [79] and traditional road vehicles [38, 71, 113, 176].

Because of the similarities with road traffic, a previous paper in this study explored the consequences of using existing urban street networks and thus 'flying-over-streets' in constrained urban spaces [53]. However, allowing high densities of drone traffic to simply operate in a constrained airspace without any imposed structure would severely impact the level of safety. To prevent the onset of conflicts, the aim of the previous study was to apply the principles of segmentation and traffic alignment to the urban airspace to organise traffic into different altitude layers with respect to travel directions.

5.2.4. ONE-WAY AIRSPACE DESIGN

Based on the findings of unconstrained urban airspace research [183, 184] and road traffic studies [72, 109, 139], we developed a one-way airspace configuration. Historically, one-way streets have been adopted as a simple and efficient measure to manage traffic safety in urban networks [178]. Here, drone flights are directly guided over one-way streets while adhering to the urban street network. To separate traffic according the four quadrants of north, east, south and west directions, the airspace is vertically segmented into a stack of direction-constrained altitude layers. In addition, a one-way directional constraint is imposed on each street, where a street will only accommodate north, east, south, or westbound traffic. This means that opposite traffic flows are not separated by means of altitude, but instead guided along (parallel) streets [53], which is comparable to one-way street traffic for on-ground traffic [72]. In this research, we use an orthogonal grid-like network, such as the Manhattan urban street network, because it is predominately optimised for one-way traffic [29].

THROUGH AND TURN ALTITUDE LAYERS

In this study, the airspace is divided into two main types of altitude layers consisting of through-layers, which accommodate through traffic; and turn-layers, which is necessary to facilitate turning traffic (see, Figure 5.1). Here, we define through traffic as traffic that travels across at least one intersection, while turning traffic is denoted by traffic that is turning at an intersection. In our experiments, turning traffic is required to decelerate and thus reduce speed to safely execute a turn at an intersection. Separating slow turning traffic from through traffic reduces the conflict probability and thus also decreases any potential disruptions between the two flows, which in turn increases the safety of the airspace. Notably, a similar design approach is seen in highway design for road vehicles [71].

ALTITUDE LAYER ASSIGNMENT

In this study, the flight routes coincide with the urban street network, i.e., the drone flights are directly guided along the streets. Hence, it is assumed that the layers are not hindered by any buildings and it only conforms to the street network.

The airspace concept in this study consist of multiple stacks of altitude layers that range from 75 to 1050 ft. Moreover, the airspace features through-layers and turn-layers that are vertically spaced at a distance of 25 ft. As a result, this implies that the airspace concept can hold 40 layers, which comprise of 20 through-layers and 20 turn-layers, respectively. Within these 40 layers, there exist 20 layers for each cardinal direction. Therefore, the number of layers depend on the assumed altitude range (i.e., 75 to 1050 ft) and the vertical separation distance of 25 ft. In Figure 5.1 we present a schematic 3D illustration of one set altitude layers that fit into the altitude range 75 to 250 ft for the one-way airspace concept. To get the complete set of 40 altitude layers, the set of eight altitude layers is repeated five times until 1050 ft [53].

Note that although different choices can be made in selecting these values, this will only affect the number of layers available to each cardinal direction. It will not change the main principle of the airspace concept. The reasons to select this particular altitude range are that the definition of clear altitude airspace for drones to operate varies with respect to region [209]. Also, the U-Space concept of operations study has not defined the boundaries of the airspace for which drones are assumed to operate [15].

The allocation of altitudes is based on the respective flight headings hence, we employ a simple altitude-heading rule to compute the flight altitudes ($h_{OW,i}$):

$$h_{OW,i} = h_{min} + \frac{h_{max} - h_{min}}{d_{max} - d_{min}}(d_i - d_{min}) \tag{5.2}$$

In the above equation, h_{max} and h_{min} are the maximum and minimum altitude of the through-layers, d_i is the shortest path distance between the respective origin-destinations. While d_{min} and d_{max} are the minimum and maximum threshold distance to the respective origin-destinations. This equation ensures that shorter flights are allocated to lower altitudes and longer flights are allocated to higher altitudes, respectively. Next, we use a basic heuristic, as illustrated by Algorithm 3, to assign the flight altitudes according to their respective heading direction. Note that ζ denotes the vertical distance (25 ft) between layers.

5

Algorithm 3: Heuristic to align flight altitudes to their travel direction.

if $315° < \psi \leq 045°$ or $135° < \psi \leq 225°$ **then**
  $h_{OW,i} = h_{OW,i}$
else
  if $045° < \psi \leq 135°$ or $225° < \psi \leq 315°$ **then**
    $h_{OW,i} = h_{OW,i} + \zeta$
  end if
end if

5.2.5. EMERGENCE IN THE ONE-WAY AIRSPACE DESIGN IN CONSTRAINED SPACES

The one-way airspace design is made up of different rules and interventions to safely facilitate large-scale drone traffic in a constrained urban environment. In particular, the altitude-heading rule and the spatial order of the urban street network is used to enforce traffic segmentation and alignment. Consequently, this requires drones to climb and descend to their respective altitudes, which in turn introduces merging conflicts. In addition, the airspace is composed of transition altitude layers to safely harbour turning flights. However, this design feature could lead to the onset of additional merging conflicts as flights need to fre-

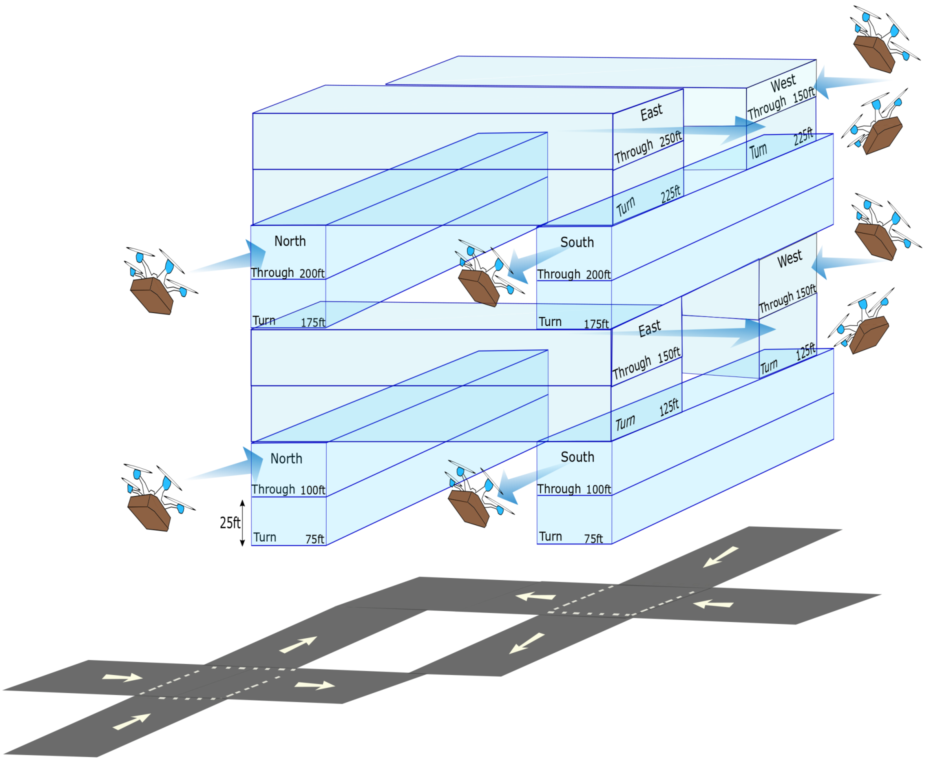

Figure 5.1: Schematic view of one set of altitude layers for the one-way urban airspace design configuration, where each altitude layer corresponds to the respective travel direction. Note that the airspace configurations consist of through-layers and turn-layers. Through-layers are used by through traffic which passes through at least one intersection. While the turn-layers are utilised by transitory flights, that is, flights that need to perform turns at the respective intersections.

quently ascend and descend from through to turn-layers and turn to through-layers before and after every heading change. Furthermore, a speed-based algorithm is used for tactical resolution which can trigger 'knock-on' conflicts. Therefore, it must be acknowledged that these seemingly simple geometrical rules on a drone and its interaction with the airspace system, can also trigger undesired emergent behaviour [87, 199].

5.3. MERGING CONFLICTS AND INTRUSIONS

In a previous study, we demonstrated that a large proportion of conflicts in the one-way airspace design is caused by merging flights, that is, drones that are climbing and descending to their respective altitude layers. In this section, we present our methodology to identify and circumvent the potential merging conflicts and intrusions. For this, we use a time-space diagram to visualise potential merging conflict and intrusion events [71, 74, 107, 109, 110, 158, 190]. In this section, we describe two merge assist policies aimed at preventing potential merging conflicts.

5.3.1. TIME-SPACE DIAGRAM

A time-space diagram is a graph that describes the position of a vehicle and its progression in time along a particular traffic stream. Time-space diagrams are typically used in road traffic engineering as a visual tool to analyse and select optimum coordination strategies for traffic signals [71]. The tool is also used in other transportation domains, such as airports to measure runway capacity [10]. Time-space diagrams are also being explored in ATM research as a controller support tool for continuous descent operations to determine the ideal separation distances for merging traffic [46]. In this study, a time-space diagram is employed to visualise the trajectories of a pair of drones and thus help circumvent a potential merging conflict, see Figure 5.2.

Figure 5.2 illustrates a typical scenario observed in the one-way airspace design. It shows a drone transitioning from its respective turn-layer to a through-layer. The diagram shows the trajectories of drone 1 (green line) and drone 2 (blue line) and their required separation margin (grey area). As drone 2 initiates a climb, the separation margin decreases hence triggering a loss of separation, as illustrated by the shaded region in Figure 5.2. The time-space diagram reveals a few approaches to mitigate the merging conflict and intrusion by influencing the trajectories of the respective drone flights. Essentially, we can influence the speeds of the drones and hence tilt and slant the lines, which effectively ensures that the drones stay within or outside the required separation margin, to circumvent a conflict. Alternatively, we can shift the lines along the time axis by imposing a delay in effort to maintain the required separation margin. Therefore, in this study we aim to influence the speed of the merging drone and also delaying the merging process in order to prevent merging conflicts.

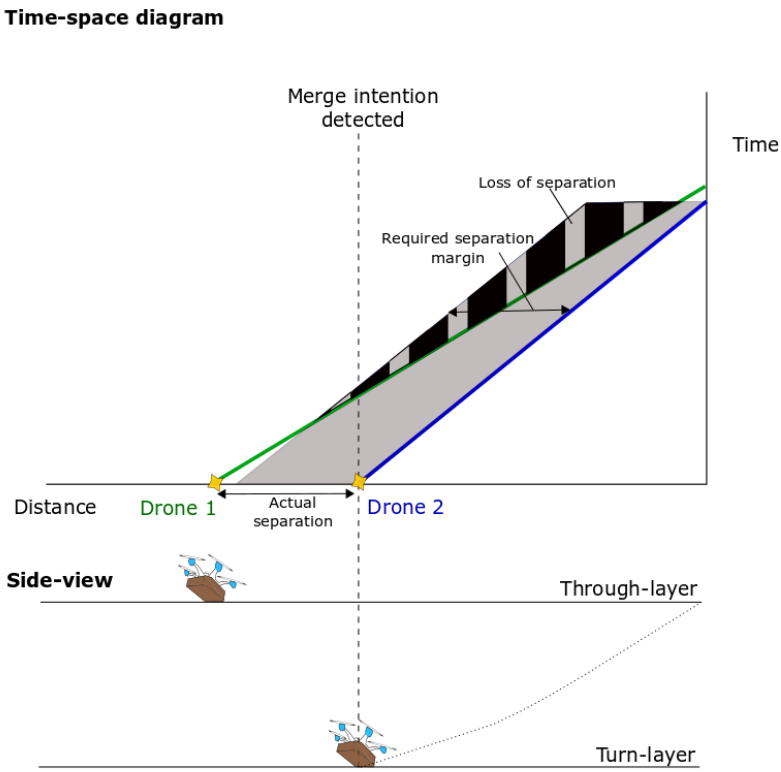

Figure 5.2: Example of a time-space representation for a pair of drones. The flight trajectories of drone 1 and drone 2 are represented by the green and blue lines. The grey area denotes the required separation margin, while the shaded area depicts a separation violation. To maintain safe separation, the trajectories need to be within or outside the required separation margin (grey area). Note that, a side-view is only included for purpose of clarity.

5.3.2. MERGE ASSISTANCE POLICIES

A safe merge event is attained by having sufficient spacing in the intended traffic flow to accommodate the merging vehicle. Here, we propose two types of merge assist policies, which is inspired by road traffic research [71, 74, 109, 110, 158], to generate sufficient spacing to form a 'gap' in the traffic stream in order to safely merge. In the first merge assist policy, we implement a speed-based strategy to generate the desired gap for traffic to safely merge, see sketch of proposed algorithm Algorithm 4. This is done by decelerating the merging drone until the desired gap is attained and thus allowing to safely merge into the respective traffic layer.

In the second merge assist policy, we employ a delay-based strategy, as summarised in Algorithm 5. This two-pronged approach influences the speed of the merging vehicle and it instructs the merging vehicle to slow-down and wait in its respective altitude layer until it is safe to merge. Then once a gap is formed, the merging drone safely transitions to its respective altitude layer. Depending on the velocity difference between the merging and non-merging drone (i.e., the vehicle in the through traffic layer), this merging drone then positions itself either behind or in-front of the non-merging vehicle. A similar approach is applied for ramp traffic that waits until a desired gap is found to enter the highway [54]. Yet, despite this similarity, road traffic and its individual drivers are able to attain the desired gaps to safely merge by using social cues and coordination, such as switching on signal indicators, making relevant eye contact and hand gestures, which are largely missing and challenging to model in autonomous systems [79, 169].

5.4. SIMULATION DESIGN

The performance of the merge assistance strategies is compared in a set of fast-time simulations, with respect to safety for low, medium and high traffic demand. In this study, we approach our experiments by first investigating the extent to which tactical conflict resolution is able to circumvent merging conflicts and intrusions. Thereafter, we augment the tactical conflict resolution with the merge assisting policies in an effort to largely reduce the merging conflicts and intrusions. In this section, we describe the design and development of our experiments used in this study.

5.4.1. SIMULATION DEVELOPMENT

SIMULATION PLATFORM

To conduct fast-time simulations, we used BlueSky [27, 85], which is an open-source Air Traffic Management simulator that has been widely employed in past ATM related studies [181, 183, 184]. The BlueSky traffic simulation tool is therefore used as the simulation platform. For the purpose of this study, we updated BlueSky's autopilot module to include elements that are specific to unmanned traffic management such as, for example, a suitable drone model and relevant drone dynamics, to account for safe manoeuvrability of flights.

A majority of drone delivery studies and also prototypes presented by drone companies mainly assume them to be multi-copters [47, 78, 111]. The primary reason for this could be attributed to the rotorcrafts' flexibility, that is the abil-

Algorithm 4: Speed-based merge assistance policy.

Data: n = number of drones; ID_k = drone identification number for all traffic $\forall_k = \{0,...,n\}$; ID_m = drone identification number for merging drones $\forall_m = \{0,...,n\}$; ID_{nm} = drone identification number for non-merging drones $\forall_{nm} = \{0,...,n\}$; m = merging drone; nm = non-merging drone; $altCur$ = current altitude; $altTar$ = target altitude; Δh = altitude difference; v_m = speed of merging drone; v_{nm} = speed of non-merging drone; τ = min gap (cruise speed × look-ahead time);

For each simulation time-step:

Retrieve all drone ID_k and get $taralt$ of next way-point;

if $|altCur - altTar|$ *for each drone >0* **then**

  Potential merge expected ;

  Get drone ID_m of merging drone;

  $ID_m \longleftarrow$ store identification number;

  for *each merging drone (m)* ID_m **do**

    Check traffic in $altTar$ of ID_m;

    Compute traffic in $altTar$ of ID_m;

    $altTar \longleftarrow$ store target altitude layer traffic;

    Get non-merging ID ID_{nm} in $altTar$;

    $ID_m n \longleftarrow$ store identification number;

    if *gap between merging m and non-merging nm* $< \tau$ *And* $\Delta h \leq \zeta$ **then**

      Potential merging conflict predicted;

      Call speed-based merge-assisting policy;

      Retrieve potential merging IDs (ID_m);

      Decelerate and choose v_m speed from ∈ [5m/s, 10.3m/s] s.t. min gap is generated;

      Check for gap generated between drone m and nm **until**;

      if *gap is sufficient to safely merge* **then**

        Return v_m to original speed assigned in flight-plan ;

      end

    end

  end

end

Algorithm 5: Delay-based merge assistance policy.

Data: n = number of drones; ID_k = drone identification number for all traffic $\forall_k = \{0,...,n\}$; ID_m = drone identification number for merging drones $\forall_m = \{0,...,n\}$; ID_{nm} = drone identification number for non-merging drones $\forall_{nm} = \{0,...,n\}$; m = merging drone; nm = non-merging drone; $altCur$ = current altitude; $altTar$ = target altitude; Δh = altitude difference; v_m = speed of merging drone; v_{nm} = speed of non-merging drone; τ = min gap (cruise speed × look-ahead time);

For each simulation time-step:
Retrieve all drone ID_k and get $taralt$ of next way-point;
if $|altCur$ - $altTar|$ *for each drone >0* **then**
  Potential merge expected ;
  Get drone ID_m of merging drone;
  $ID_m \longleftarrow$ store identification number;
  for *each merging drone (m)* ID_m **do**
    Check traffic in $altTar$ of ID_m;
    Compute traffic in $altTar$ of ID_m;
    $altTar \longleftarrow$ store target altitude layer traffic;
    Get non-merging ID ID_{nm} in $altTar$;
    $ID_m n \longleftarrow$ store identification number;
    if *gap between merging m and non-merging $nm < \tau$ And $\Delta h \leq \zeta$* **then**
      Potential merging conflict predicted;
      Call delay-based merge-assisting policy;
      Retrieve potential merging IDs (ID_m);
      if *Check $altCur$ is current turn-layer* **then**
        Stay in current turn-layer;
        Decelerate and choose v_m speed from $\in$ [5m/s, 10.3m/s] s.t. min gap is generated;
        Check for gap generated between drone m and nm **until**
        if *gap is sufficient to safely merge* **then**
          Return to original flight-plan ;
        end
      end
      if *$altCur$ is current through-layer* **then**
        Decelerate and choose v_m speed from $\in$ [5m/s, 10.3m/s] s.t. min gap is generated;
        Check for gap generated between drone m and nm **until**
        if *gap is sufficient to safely merge* **then**
          Return to original flight-plan ;
        end
      end
    end
  end
end

ity to hover and easily manoeuvre the complex urban landscape compared to fixed-wing drones. Therefore to be in-line with past research, we employ a multi-copter drone model in this study. In particular, we use the DJI Matrice 600 Pro hexacopter which can be easily modified to transport packages. The characteristics of this drone model are presented in Table 5.1.

Table 5.1: Performance data for DJI Matrice 600 Pro used in the simulations of this study.

Parameter	**DJI Matrice 600 Pro**
Speed [m/s]	5-10.3
Vertical speed [m/s]	-5-5
Mass [kg]	15
Maximum bank angle [°]	35
Acceleration/deceleration [m/s^2]	3.5

TESTING REGION

In this study, we investigate the performance of the merge assistance strategies for the one-way urban airspace concept. To simulate a constrained urban environment we apply the urban airspace concept to the urban street network of Manhattan, New York city (see Figure 5.3). There are three main advantages for selecting Manhattan as our testing region. First, Manhattan has an orthogonal network structure and thus it contains fewer dead-ends, more four-way intersections and less-winding street patterns [29]. In comparison to other cities, such as Paris or Rome, the highly-ordered grid-like street orientations of Manhattan will reduce ambiguities in our findings [30, 75]. Second, Manhattan is widely being utilised by advanced air mobility studies as a testing region in their simulations [9, 154, 155]. Third, the construction of new streets are increasingly orthogonal in nature [16, 17, 19]. Therefore, the findings of this study would still be valid in future cities.

CONFLICT DETECTION AND RESOLUTION

In our study, a 'state-based' conflict detection method is employed to identify potential separation violations [87, 90]. This was done by linearly extrapolating the drones' state within a prescribed 'look-ahead' time. Using a linear extrapolation method means that there is a likelihood that false conflicts could be detected and therefore it would need to be identified in the post-processing phase of this study. In addition, we employ separation requirements of 82 ft and 24 ft for the respective horizontal and vertical separation boundaries. The above separation

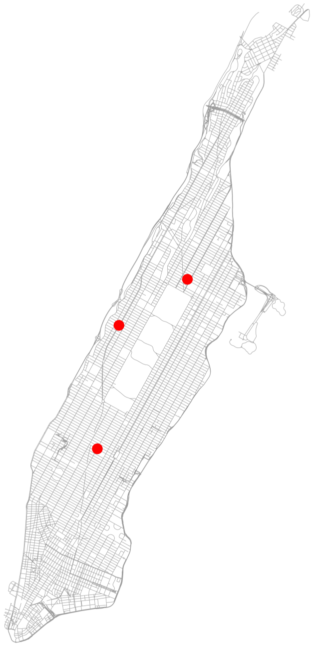

Figure 5.3: Urban street network of Manhattan, New York City (with area size of 59.1 km^2), obtained from OpenStreetMap [77] via OSMnx Python library [28]. The three red dots represent the (approximate) location of chosen drone depots in our study.

requirements were adopted based on trial experiments since no formal separation distance standards have been established for autonomous delivery drone flights in constrained outdoor environments. A prior study employed horizontal separation values of 105 ft and 164 ft ([13, 156]), while other studies have used values ranging between 16 to 984 ft for the vertical separation requirement [33, 162]. Note that the separation distance can affect the proper functioning of conflict detection and resolution in constrained airspace, through its relationship with aspects such as the traffic density, the performance characteristics of the drones and the topology of the network, for example, the length of the streets. For the experiment area of Manhattan, the majority of the street lengths range between 17 to 140 ft. With larger horizontal separation distances, the linear state-based conflict detection method would detect false conflicts which do not even result in a loss of separation because of the topology of the airspace structure. Therefore, in this study, the horizontal separation distance of 82 ft and vertical separation distance of 24 ft proved optimum in terms of the number of losses of separation prevented and the false conflicts detected. The detected conflicts are then resolved in a pair-wise manner using a basic (1-D) speed control algorithm, as described in Algorithm 6.

Algorithm 6: Basic (1-D) speed control conflict resolution.

```
Data: n = number of drones; v_j = speed of drone j; nconf = number of
      conflicts; confpair = conflict pair of i, j where i is the leader
      drone and j is the follower drone;
Require n, v_j ∀ j = {1,...,n}
Compute and get nconf and conflict pairs from state-based conflict
  detection
if nconf > 0 then
  | for all conflict pairs get drone j of conflict pair (→ compute new v_j) do
  |   | if confpair i, j in current conflict then
  |   |   | change v_j to have speeds from ∈ [ 5m/s, 10.3m/s] s.t. min
  |   |   |   separation is respected between drone i and j ;
  |   |   | if confpair i, j not in current conflict then
  |   |   |   | Return j to original speed assigned in flight-plan ;
  |   |   | end
  |   | end
  | end
end
```

5

ONE-WAY AIRSPACE CONCEPT IMPLEMENTATION

The network geometries of Manhattan were extracted from OpenStreetMap (OSM) [77] using the OSMnx Python package [28], which provides an interface to query OSM data. We then used the OSMnx package to extract nodes and edges to generate a graph for Manhattan. The network graph of the one-way concept featured a directed graph and thus it enforces the streets to be one-way.

Three depot locations were chosen for this study that were based on initial experiments that demonstrated convergence of traffic flow. During the simulation, all drone flights depart from one of the three depots (Figure 5.3) to their respective destinations, which includes a set of uniformly distributed destinations that adhere to the drones' minimum and maximum range limit of 1 km and 10 km. Note that this study does not consider take-off and landings phases and it only considers en-route flights phases.

Therefore, in this study each drone in the simulation is created at its respective cruising altitude at each of the three depots. Then, the respective drone follows its respective flight-plan and flight-route. Based on the respective depot location and the destination, we computed the shortest paths using the method described in [76]. Each shortest path consisted of a set of geographical coordinates which were used to determine the bearing (heading direction) of each of the streets along the shortest path; and the distance of the shortest paths. Once the drone arrives at its respective destination location it is deleted from the experimental area.

5.4.2. INDEPENDENT VARIABLES

Three independent variables were considered in this study:

1. airborne separation assurance conditions: with and without tactical conflict resolution;
2. merge assistance strategies: speed-based and delay-based assistance; and,
3. traffic demand: low, medium, and high traffic densities.

In this work we base the traffic demand on food-delivery scenarios [51]. Such applications are widely been investigated by startups and large technology companies. Table 5.2 summarises the traffic demand scenarios used in this study for the city of Manhattan which encompasses an area of 59.1 km^2. Note that even though in this case, food delivery is chosen as a scenario, this traffic demand could also represent different applications, such as parcel delivery, or a potential medical-delivery scenario, in which drones rapidly deploy vaccines, or any other time-sensitive medical material, to patients or between hospitals [125].

The combination of the three independent variables results in 12 experimental conditions. Each condition is performed with five different traffic realisations, resulting in a total of 60 simulation runs (two conflict resolution conditions × two merge assistance strategies × three traffic demand cases × five repetitions). The randomisation between traffic realisations was performed by uniformly and randomly generating origin-destination pairs between depots with distances ranging from 1 km and 10 km for the city of Manhattan.

5.4.3. DEPENDENT MEASURES

In this study, we consider several dependent measures relating to safety, which consist of the total number of pairwise conflicts and intrusions, to evaluate the performance of the merge assist policies.

Table 5.2: Traffic density characteristics of the three demand scenarios for the simulation area of Manhattan, New York City, network consisting of an area of 59.1 km^2.

	Low	**Medium**	**High**
Traffic density (drones/km^2)	31	46	61
Inflow rate (drones/min)	30	45	60
Hourly demand (drones/hr)	1800	2700	3600
Demand per depot (drones/depot)	600	900	1200

SAFETY

The safety of the airspace is measured in terms of the total number of pairwise conflicts and intrusions. In this study, a better merge assist policy is determined by fewer conflicts and intrusions. Here, an intrusion, or loss of separation, occurs when there is a violation of the minimum vertical and horizontal separation requirements. Here, a conflict is a predicted loss of separation within the predefined look-ahead time. For our experiments, we employ a look-ahead time of 10 s. A look-ahead of 10 seconds implies that the drones need to look-ahead at a distance of about 100 m when cruising. This look-ahead time is tuned to the average length of the street for the experiment area of Manhattan. With a larger look-ahead time the state-based conflict detection would look at distances beyond the average street length, thus triggering many false conflicts. As a result, in our study, a look-ahead time of 10 s demonstrated the optimum balance between the number of false conflicts being detected and the number of intrusions prevented in a trial simulation experiment.

DISTANCE BETWEEN THE NEAREST DRONE PAIR ON THE SAME ALTITUDE LAYERS

Here, we capture the distance to the nearest drone within the same altitude layer per street, for low, medium and high traffic demand. We use this metric to understand the distance distribution of pairs of drones that fly at distance smaller than horizontal separation distance (82 ft) in all directions. We speculate that pairs of drones that fly below this threshold value have limited manoeuvrability for safe merging.

TRAFFIC ACCUMULATION PER STREET

Together with the distance between the nearest drone pair mesoscopic property, we also measure the accumulation of traffic on a particular street, that is, the number of drones flying over a street within its respective altitude layer. During the initial simulation phase, we observed some streets that experienced disproportionately higher traffic flows. To quantify the traffic flow in such streets, we measured the local traffic flow in three particular streets, namely street A, B and C, in our experiment region.

5.4.4. EXPERIMENTAL HYPOTHESES

Our working hypothesis related to this study is that larger number of conflicts, intrusions and conflict chains would be seen with increasing traffic demand. Further, we hypothesise that applying the delay-based and speed-based merge assist policies, along with tactical conflict resolution, would demonstrate a marked decrease in the total number of conflicts and intrusions for low, medium and high traffic demand cases. In addition, we hypothesise that the speed-based merge assist policy would have better performance than the delay-based policy. Because in the delay-based merge assist policy, a merging flight has to lower its speed and thus prolong its time spent in the turn-layer until it is safe to merge and thus as traffic density increases, it is likely that a larger proportion of in-trail conflicts would be triggered.

5.5. RESULTS

The experimental results of this study are presented in this section. The effect of the independent variables on safety is illustrated using stacked bar charts, scatter plots and box-and-whisker plot. The different categories of conflicts and intrusions is depicted using stacked bar charts, and the spatial distribution of intrusions is illustrated with scatter plots. The box-and-whisker plot presents data on the distance between the nearest drone measure. In the box-and-whisker plot, we display the median line; interquartile range (IQR), which is captured by the bounds of the box and represents the 25-75th percentile; the minimum and maximum distribution of the data is denoted by the whiskers; and, the points greater than $\pm 1.5\times$IQR represent outliers.

5.5.1. TOTAL NUMBER OF CONFLICTS AND INTRUSIONS

Here, we present our results for the total number of pairwise conflicts and intrusions in the one-way airspace design and its effect to the tactical conflict resolution. Figures 5.4 and 5.5 therefore depicts these safety metrics for the one-way urban airspace concept for low, medium and high traffic demand cases. In this study, a pairwise conflict and intrusion is accounted only once during the simulation, while a repeating pairwise conflict and intrusion is recounted, independent of it duration. Figure 5.4 illustrates an increase in the total number of pairwise conflicts with increasing traffic demand. This same trend is observed in the total number of pairwise intrusions, as shown in Figure 5.5.

In addition, Figures 5.4 and 5.5 demonstrate the effect of the airborne separation assurance conditions which represent with (CR ON) and without (CR OFF) tactical conflict resolution for the one-way concept. The Figures 5.4 and 5.5 also indicate the composition of the conflicts and intrusions to gain a deeper understanding in the total number of in-trail, crossing and merging conflicts and intrusions. In Figure 5.5, we observe that as expected, the total number of intrusions is significantly reduced with tactical conflict resolution. Conversely, an opposite trend was seen in the total number of conflicts. With tactical conflict resolution, the total number of conflicts increased across all three traffic demand cases. This effect is caused by a lack of manoeuvrability for resolution manoeuvres as result of the highly constrained airspace design. Therefore, the increased structuring of the airspace increases the probability of encountering other drones when tactical conflict resolution is engaged and it eventually leads to conflict chains and and thus secondary conflicts. Note, however, that such knock-on effects are inherent to decentralised reactive systems. [90, 99, 112, 173, 181]. In fact, even centralised separation strategies can trigger secondary conflicts with increasing traffic density [112]. Yet it is not necessarily the case that these secondary conflicts are destabilising and detrimental to safety. Their effect can also be positive, by communicating the intent to resolve and thus help to create more of a stabilising effect on the airspace [90]. Secondary conflicts are also observed in road traffic for which they also provide a beneficial effect [102, 143].

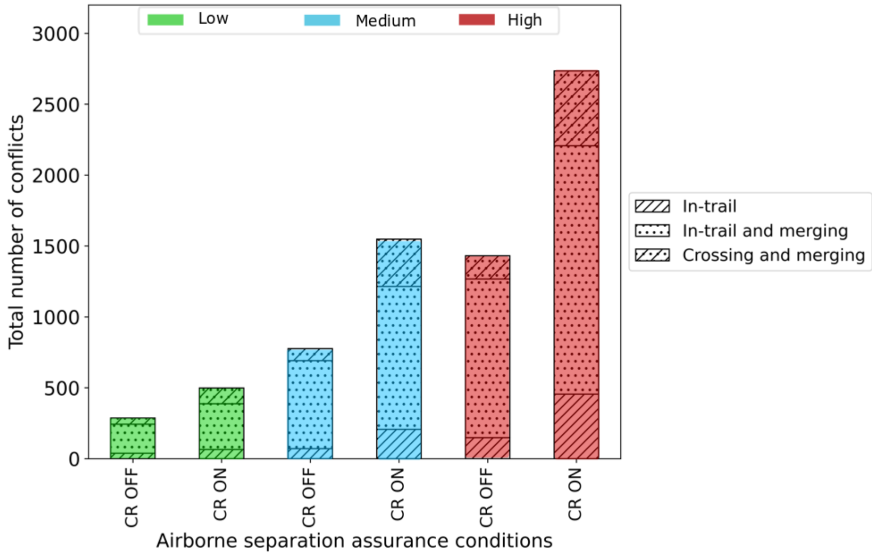

Figure 5.4: The total number of pairwise conflicts and their associated type with (CR ON) and without (CR OFF) tactical conflict resolution for low, medium and high traffic demand.

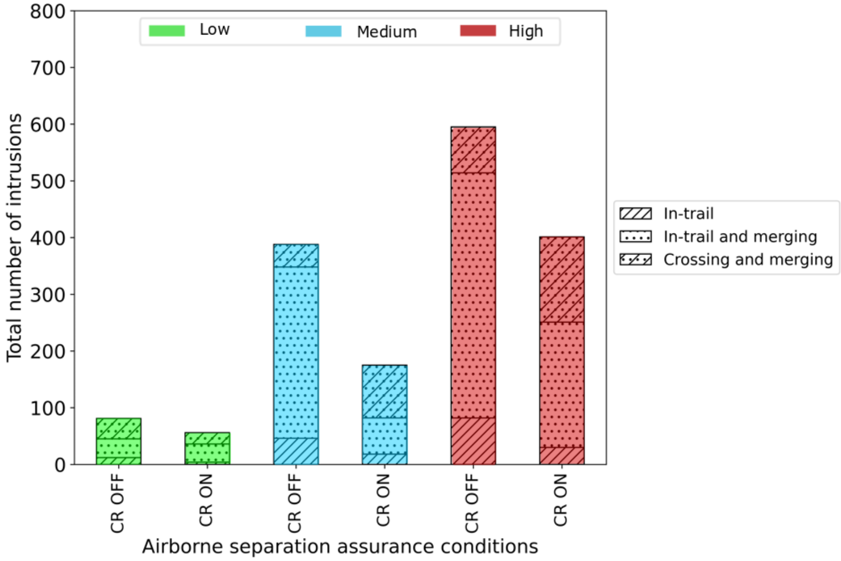

Figure 5.5: The total number of pairwise intrusions and their associated type with (CR ON) and without (CR OFF) tactical conflict resolution for low, medium and high traffic demand.

5.5.2. EFFECT OF MERGE ASSISTANCE STRATEGIES ON THE TOTAL NUMBER OF CONFLICTS AND INTRUSIONS

We, next present the findings for merge assist policies. Figures 5.6 and 5.7 display the effect of the speed-based and delay-based merge assistance polices on the total number of pairwise conflicts and intrusions for low, medium and high traffic demand scenarios. Note that in all three cases (i.e., MA OFF, MA DELAY and MA SPD) we consider the effect with tactical conflict resolution switch on (i.e., CR ON). In addition, the bar charts categorise and display the proportion of in-trail and crossing types of conflicts and intrusions for level and merging flights. The bar charts show that the conflicts and intrusions are primarily generated by flights that are transitioning to their respective altitude layers because of the large proportion of merging conflicts and intrusions.

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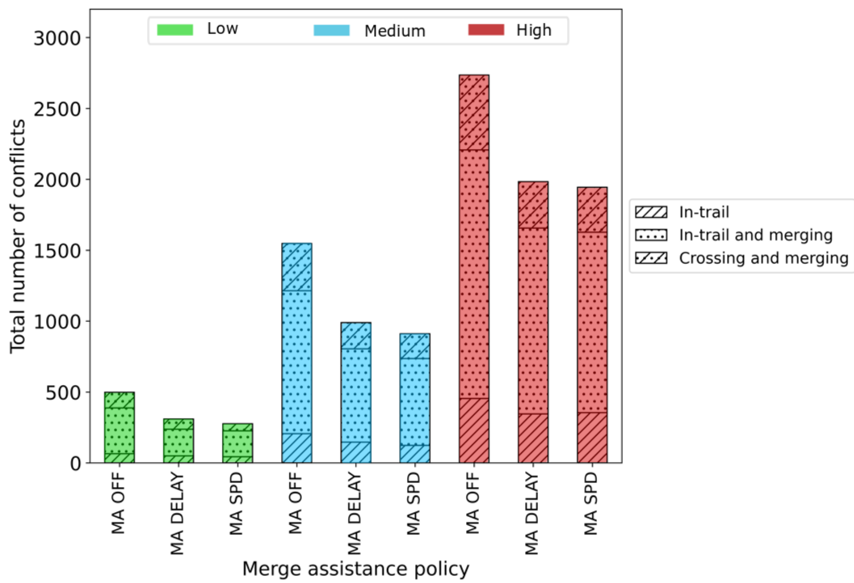

Figure 5.6: The total number of pairwise conflicts and their associated type with and without merge assistance for low, medium and high traffic demand. Note that MA OFF means without merge assistance. All three cases (MA OFF, MA Delay and MA SPD) also consider the effect of the tactical conflict resolution.

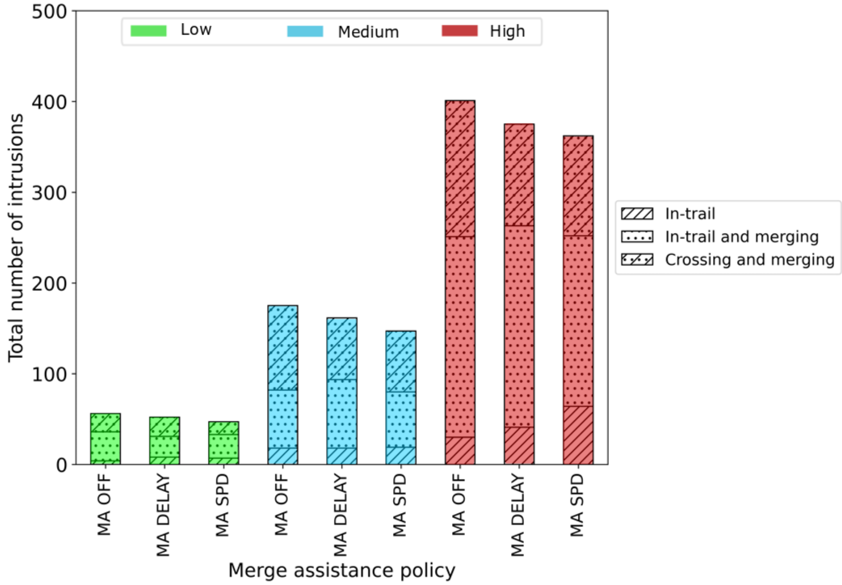

Figure 5.7: The total number of pairwise intrusions and their associated type with and without merge assistance for low, medium and high traffic demand. Note that MA OFF means without merge assistance. All three cases (MA OFF, MA Delay and MA SPD) also consider the effect of the tactical conflict resolution.

5

Figure 5.6 shows a modest decrease in the total number of conflicts with delay-based and speed-based merge assistance. In comparison to the scenario of without merge assistance, the total number of conflicts in the delay-based merge policy depicts a 28-38 percent decrease from low to high traffic demand, while a 29-44 percent decrease is shown in the speed-based merge policy, for low to high traffic demand. In terms of the categories of conflicts, Figure 5.6 mainly indicated a decrease in the in-trail and crossing types of conflicts when merging.

Similarly, the bar chart in Figure 5.7 demonstrates a less modest decrease for the total number of intrusions in the delay-based and speed-based merge assistance policies. As initially hypothesised, the speed-based policy more effectively reduces the total number of intrusions than the delay-based policy. Compared to the without merge assistance scenario, the delay-based policy demonstrates a decrease of 6-8 percent in the total number of intrusions for the low to high traffic demand, while the speed-based policy shows a decrease of 9-16 percent in the total number of intrusions for low to high traffic demand. In terms of categories of intrusions, we see a slight decrease in the number of intrusions for crossing and in-trail merging flights. However, with higher traffic demand, the number of in-trail type intrusions increases which could be related to the longer merging process hence creating bigger speed differences between a pair of drones. Nevertheless, the figures show that the speed-based policy has better performance than the delay-based policy. The better performance can be attributed to the decrease in in-trail conflicts and intrusions when merging since drones do not have to remain in the turn-layers for a safe merge opportunity.

5.5.3. SPATIAL DISTRIBUTION OF INTRUSIONS WITHOUT AND WITH MERGE ASSISTANCE

We next examined the location of pairwise intrusions without and with merge assistance to determine the potential cause of any unresolved intrusions. To analyse this, we overlaid the exact geographical coordinates of each pairwise intrusion for all three traffic demand scenarios over our experiment area to locate where these intrusions take place. The charts in Figure 5.8 represent the geographical location of pairwise intrusions without any merge assistance and with merge assistance for the high traffic density scenario. The plots suggest that most intrusions remain unresolved even with the use of merge assistance at particular locations in the street network. These unresolved intrusions are mainly located in certain hotspot regions, which have a high concentration of intrusions, as seen in the charts. Therefore, the results indicate that the location and geometry of the street network strongly influence the efficacy of the merge assist policies. Hence, to further investigate the latter, we look at the network on a mesoscopic level and thus inspect specific streets that display hotspots.

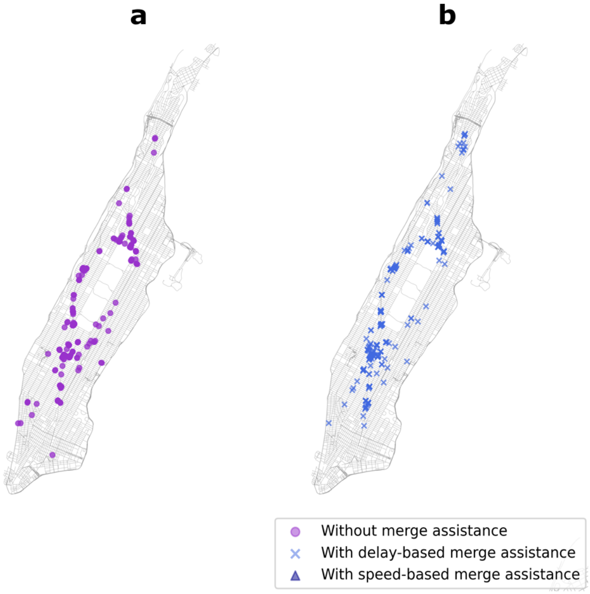

Figure 5.8: Here **a**, **b** and **c** geographical location of pairwise intrusions that relate to without merge assistance, with delay-based merge assistance and with speed-based merge assistance with respect to the high traffic density scenario. Colours are used to distinguish the different pairwise intrusion categories: without merge assistance marked in purple (**a**); delay-based merge intrusions represented by the blue crosses (**b**); and the speed-based merge intrusions marked by the blue triangles (**c**). The overlaid intrusions from the different merge assist policies indicated by the darker hotspot zones demonstrate that some intrusions remain unresolved.

5.5.4. MESOSCOPIC TRAFFIC OBSERVATIONS

We next explored why most intrusions remained unresolved in some portions of the urban network. By investigating the mesoscopic nature of the airspace concept, we uncover that a majority of unresolved intrusions mainly exist in busy streets for which the average distance between the nearest drone is less than the horizontal separation distance of 25 m which is used in our study. These busy streets are identified using a heatmap, as shown in Figure 5.9. The heatmap illustrates a few hotspot regions. Note that the heatmap is generated using a geographic spatial software [64] that uses the Kernel Density Estimation (KDE) to create the heatmap and setting the search radius (bandwidth) of the KDE to 100 m with a quartic kernel density (i.e., only coordinates within this search radius is used to estimate the KDE and thus generate the heatmap) [40, 208]. Here, we examine one specific hotspot area in our experiment, which is depicted in Figure 5.10. In particular, the charts show a hotspot street where intrusions are largely prevalent even with the use of merge assist policies.

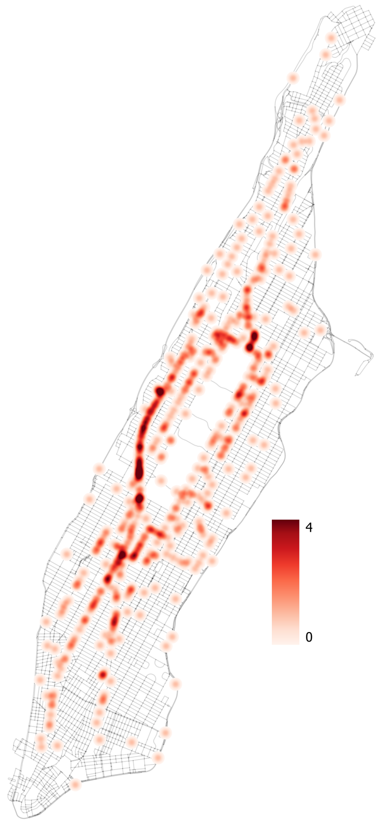

Figure 5.9: Traffic density heatmap of Manhattan urban network. The colour ramp depicts the traffic density from 1 to 4 drones per street within a search bandwidth of 100 m. The dark red region represent high volume of traffic, whereas the faded coloured regions indicate low volume of traffic.

In Figure 5.10, street 'A', which comprises of a length of approximately 63 m, indicates that the nearest drone within the same layer is below the horizontal separation distance of 25 m, as illustrated by the median of the box-and-whisker plot in Figure 5.10b. Additionally, Figure 5.10c depicts the traffic density of the street that demonstrate, on average, some layers experience between two to four drones within the street at a particular instance in time. Note that the localised concentration of traffic on particular streets, which cause high traffic densities, is attributed to a specific property of the urban street network [20, 21, 23, 106] and thus the results illustrate that the current routing scheme should also incorporate traffic density in its cost function to prevent traffic hotspots. Therefore, the above findings suggest that there is limited manoeuvrability space for safe merging.

Furthermore, the simulation results tell us that the topology of the street network should also be taken into account when assessing the performance of the merge assistance policies. In particular, we noticed that the influence of the street network topology, i.e., the length of the streets and the higher number of turns associated with the flight-plans determine whether there is insufficient time for the merge assistance policies to fully respond and thus resolve any merging conflicts.

To investigate this observation, we present a graphical explanation (Figure 5.11) on why the merge assistance policies might be less effective on short-distance streets. As illustrated in Figure 5.11, drone 2 merges into the target altitude layer 925 from layer 900. Subsequently, there is also traffic (drone 1) in the target altitude layer, which triggers a merging conflict and intrusion. Due to the relatively shorter distance of the street, the merge assistance policy has insufficient time to resolve the merging conflict before drone 1 leaves the target altitude layer and turns at the intersection in order respect its flight-plan and the topology of the street network. We believe that the inability of the merge assistance policies to completely resolve the conflict and intrusion in short-distance streets could be limiting the effectiveness of the policies.

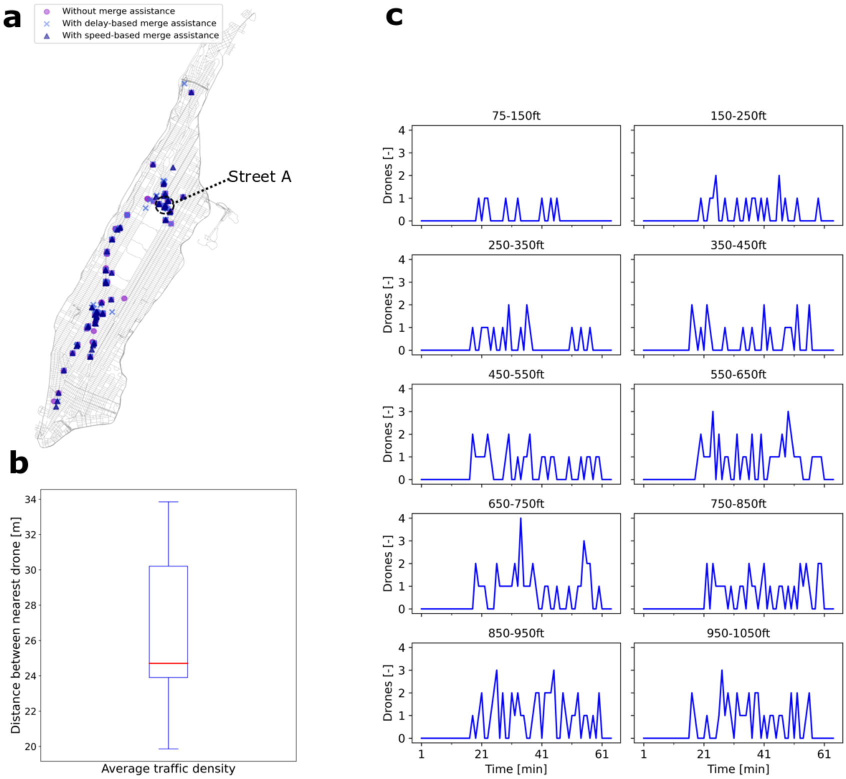

Figure 5.10: The urban network of Manhattan. **a**, We overlaid the pairwise intrusions associated without any merge assistance and with delay-based and speed-based merge assist policies. Colours are used to distinguish the different pairwise intrusion categories. The purple marker represent the pairwise intrusions without any merge assistance; the blue cross represents the pairwise intrusions associated to the delay-based merge assist policy; and, the blue triangle marks the pairwise intrusions caused by the use of the speed-based merge assist policy. The darker regions indicate the presence of pairwise intrusions even with the use of delay-based and speed-based merge policies. The map indicates hotspot street at which intrusions are largely prevalent. We identify the street as 'street A' which has a length of 62 m. **b**, We capture the distance between the nearest drone flying over street A using a box-and-whisker plot. The plot shows that the median is below the horizontal separation margin of 25 m. **c**, In addition, we capture the traffic accumulation on this particular street. The line plots show that there are instances when there are between two to four drones on the same layer flying over the street.

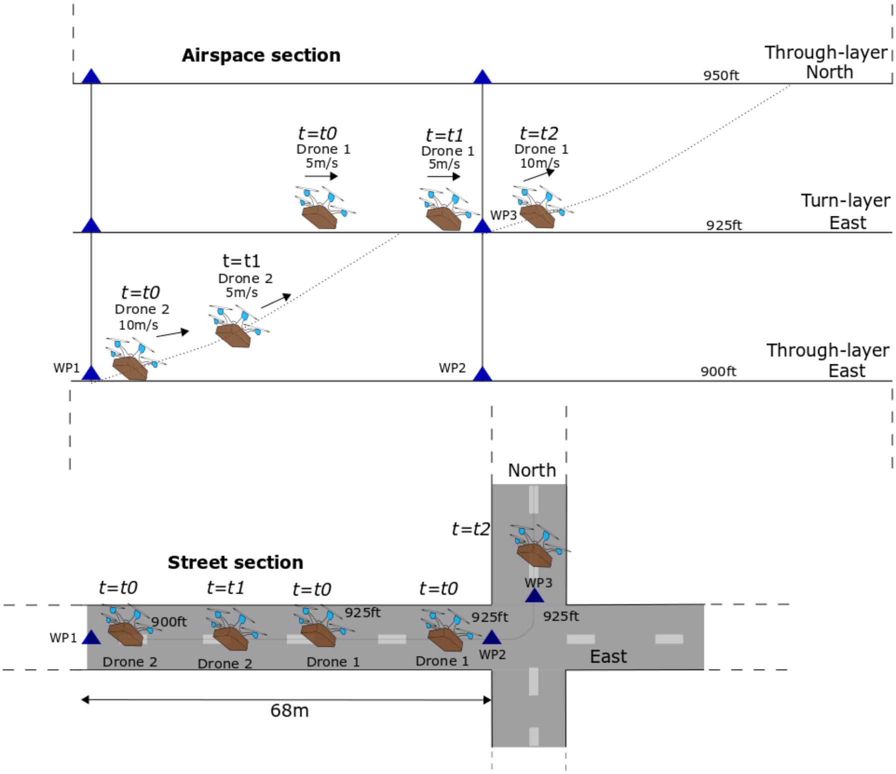

Figure 5.11: Graphical explanation on a typical short-distance street that shows the merge assistance policies to be less effective because of the inability of the merge assistance policies to respond and resolve any merging conflicts.

5.6. DISCUSSION

Drone-based deliveries are expected to operate in high densities of traffic within constrained urban environments. Last-mile deliveries of small express packages and time-sensitive medical supplies such as vaccines are examples of potential candidates for drone-enabled deliveries. A previous study explored a novel implementation of one-way and two-way streets in combination with altitude-heading rules in an effort to mitigate conflict probabilities [53]. The study was performed on the urban network of Manhattan in order to simulate a constrained airspace. The topography of Manhattan resulted in several turns associated with each flight-plan and the use of flight-levels, created a large number of merging flight events that required to transition to their respective altitude layers. These merging flights generated the majority of the conflicts and intrusions, especially in close proximity to intersections. However, these merging conflicts were expected since the tactical conflict resolution algorithm had no prior information of potential merging encounters. To improve the safety of the urban airspace design for large-scale drone traffic, this study investigates two merging policies inspired by road traffic studies [109, 158, 202].

In this research, we apply the one-way airspace design to the urban street network of Manhattan, New York, with an area of 59.1 km^2. We applied a delay-based and a speed-based merge assist strategy in an attempt to reduce the onset of conflicts and intrusions caused by merging flights. Using randomised fast-time simulations, we examined the performance of the merge assist policies with respect to safety. Here, we compared safety in terms of the total number of pairwise conflicts and intrusions (losses of separation). Our results indicate that the delay-based and speed-based merge assist policies are capable of reducing the total number of pairwise conflicts and intrusions, but not to a large extent. The results show that the speed-based merge assist policy has a slightly better performance over the delay-based policy. Further, for both policies we observe a decrease in the number of in-trail and crossing merging conflicts and intrusions. Yet, despite this decrease, no dramatic reduction in the total number of intrusions is observed.

The meagre reduction to total number of conflicts and intrusions is caused by the limited space to safely merge. These merging events are largely caused by flights that are either climbing or descending to their respective altitude because of the imposed altitude-heading rules and the presence of frequent turns associated to the structure of the airspace. A previous study showed that there are nearly seven turns per flight-plan for the one-way concept [53] and thereby increasing the probability of conflicts. Similar to road traffic, merge conflicts represent a large percentage of highway collisions [210]. Generally, such merge conflicts are caused by insufficient gaps in the flow of traffic due to high-density of traffic on a particular road segment [109]. In addition, in our study, the merge assist policy only influences the merging vehicle. However, for an effective merge, even the non-merging vehicle should equally be influenced by the merge assist policy, such as, for example, reducing its speed and thus giving way to merging traffic. These types of operational behaviours are commonly found in current road transport where important social cues play a critical role in ensuring a safe merging event [79, 169].

To understand the underlying reasons behind the low efficacy in merging intrusions, we investigated three specific streets in our experimental area. By overlaying the locations of intrusions culminating without any merge assistance and with delay-based and speed-based merge assist policies. Even with the use of merge assistance, we identified a number of unresolved intrusions. By examining the urban network through a mesoscopic scale, our results point to two main reasons for the existence of these unresolved intrusions. First, our results show that these particular streets (comprising of lengths between 62 to 72 m) experience high localised traffic flow. Such localised concentration of traffic flow is caused by a particular network property known as high betweenness centrality [20, 21, 23, 106]. This means that some links or streets experience a disproportionately higher number of traffic flow as a consequence of greater number of shortest paths passing through a particular street [106]. In general, this could also represent of a real-world feature, in which a fleet of drones travel more frequently to a specific destinations due to higher demand. In our study, a drone needs to adhere to a horizontal separation of 25 m (82 ft) in each direction. Therefore, for a relatively shorter street, only one drone can safely be accommodated in its respective altitude layer within the street at any instance in time. Interestingly, our results show that there are instances when there are even four to six drones occupying these particular streets. Second, our results also demonstrate that the distance between the nearest drone on the same altitude layers is far below the horizontal separation margin. Findings of such emergent properties of high localised traffic flow together with smaller distances between drones hence, suggest that there is insufficient manoeuvrability space for safe merging, which in turn causes the merge assistance to be less effective in these types of scenarios. In addition, our observations indicate that the large proportion of short-distance streets and the higher number of turns per flight could be a key factors that limits the merge assistance strategies to fully resolve any conflict and intrusions within a given altitude layer. Future research should therefore investigate the performance of the proposed merge assistance policies on an urban network that consists of long-distance streets and with limited number of turns.

In this research we employed a fixed separation margin. However, when compared to road transport, particularly, highway traffic, drivers and advanced adaptive cruise control systems employ a more flexible and dynamic approach to determine a safe horizontal separation margin. For example, on-ground vehicles use the notion of time headway as an important variable for safe distance keeping [12, 135, 174], which is computed by dividing the distance to a lead vehicle by the speed of the following vehicle [174]. The time headway varies with respect to the traffic density, for example, on the highway, in sparse traffic states, larger (>4 s) time headways are observed, while smaller time headways (1 - 2 s) are experienced in relatively dense traffic states, such as merge lanes and in urban areas [12, 135, 174]. In this context, dynamic time headways allow for higher traffic capacity and safety levels [131]. Future research should therefore investigate similar approaches. One starting point for further research is to incorporate and experiment with smaller horizontal separation margins in the turn-layers where average traffic speeds are relatively low, and hence we anticipate a marked increase to the efficacy of the merge assist policies. Similarly, the urban street network consist of different street lengths which might impact the efficiency of the merging policies, future studies should investigate the possibility of developing a merging policy that adapts to the different street lengths. In addition, future studies should investigate methods to proactively manage traffic flow congestion by incorporating strategic flow control [41] or an individual metering strategy to regulate traffic flow [110]. By gaining inspiration from autonomous vehicle research, future work should also study the notion of congestion-aware routing schemes by including the current traffic density of a given route in the cost function in an effort to circumvent the onset of congestion on typical busy streets [164]. Alternatively, further studies should explore a variety of different routing algorithms, such as simplest paths or minimum travel time paths [76, 200] as a way to decrease the number of turns, which would reduce the number of merging flights and thus mitigate the probability of conflicts. Another interesting avenue is to extrapolate our methods to dynamic airspace configurations, that is, airspace structures that evolve over time based on traffic demand. Current operations of express package delivery of meals and medicine represents a dynamic nature and thus they will require a flexible airspace design.

Our results are subject to some limitations. First, our simulations do not include all real-world features that are relevant to the safe accommodation of large-scale drone delivery operation in highly constrained cities. Meteorological events, such as rain and hyperlocal wind could orchestrate localised traffic congestion by concentrating traffic to specific areas and thus decreasing the overall safety of the airspace. Second, the conflict detection algorithm employed in our experiments linearly extrapolates the drones' states by a prescribed look-ahead time. This obviously has the tendency to trigger false conflicts which may impact the overall safety of the airspace. Future studies should therefore take into account the drones' intent and flight-path information in order to circumvent false conflict detections. Third, the experiment area used in this study comprises of an orthogonal street network. Thus, our findings should be interpreted with due caution when comparing to other types of street networks (see, for instance, [16, 17, 19]). To address this limitation, research has already begun to explore these findings to non-orthogonal street networks [13].

5.7. CONCLUSIONS

The possible advent of delivery drones in cities could change the face of urban last-mile delivery. Drone-based delivery could pose as a better alternative, in terms of cost and energy efficiency, than current transport modes, such as vans and bikes. Yet, society might only benefit from drone deliveries if and when they are able to operate in high densities of traffic, which in turn could lead to several challenges. Here, we aimed to address one main challenge, that is the ability to safely harbour such large-scale drone traffic operations in heavily constrained urban environments. In this context, the current research sheds light on our understanding on the intricate safety properties of operating high traffic densities of autonomous drones in a constrained urban airspace. To this end, we structured and organised the urban airspace of an orthogonal street network with horizontal constraints in an effort to promote one-way traffic flow. In addition to the horizontal constraints, the one-way airspace concept also featured vertically segmented altitude layers to accommodate traffic with similar directions and thus lowering the risks of conflict. By testing the airspace design with three levels of drone delivery traffic densities for the urban street network of Manhattan, New York, our results showed that most conflicts and losses of separation occur during the merging phase. Fundamentally, this means that by introducing altitude-heading rules to structure traffic and thus mitigate conflicts, shifts the occurrence of conflicts to the merging phase. To circumvent the occurrence of merging conflicts and intrusions, we employed a delay-based and speed-based merge-assisting strategy. Our results demonstrated that merge assistance is able to reduce conflicts and intrusions, but to a much lesser extent than anticipated. To explain this relatively low efficacy, we investigated key mesoscopic features, such as hotspot regions that showed high localised traffic flow on particular busy streets of the network; and thus the data suggests that there is insufficient space to safely merge and the inability for the strategies to fully respond and thus resolve conflicts on short-distance streets. Though the urban airspace concept and merge assist strategies still needs to be investigated for other types of urban networks, and further improvements remain to be done, the findings presented in this study could be useful for advanced air mobility designers and unmanned traffic management policymakers.

6

DISCUSSION AND CONCLUSIONS

This chapter revisits the research questions and presents a discussion of the main findings of this thesis. Based on the discussion, concise conclusions are drawn. The chapter also elaborates on the modelling assumptions used in this thesis and how they affect the conclusions of this work. Finally, the chapter lays out a set of recommendations for future research and outlines the societal impact of this research.

6.1. OVERVIEW

In this dissertation, we investigated urban airspace designs for the purpose of safely facilitating high-density drone delivery traffic in a highly constrained environment. We began by briefly describing the challenge of designing such infrastructure to support these high-density advanced air mobility concepts in constrained spaces. We argued that many of the design paradigms and philosophies used in unconstrained airspace design and road traffic engineering research can be leveraged for the purpose of designing an airspace structure for high-density delivery drones. To achieve this goal, we enlisted four research questions in Chapter 1, where each question was individually addressed in four research chapters. The first research chapter (Chapter 2) explored what factors influence the traffic density estimates of drone deliveries for a typical urban environment. Once we understood how much traffic demand is to be expected in a constrained urban airspace, we then examined two seemingly different airspace configurations in effort to support and safely harbour high-density drone traffic, as presented Chapter 3. Both airspace concepts were applied to an orthogonal urban street network in order to simulate traffic flow in a constrained urban environment. Next, in Chapter 4, we investigated the intricate safety properties of the proposed airspace concepts. Our analysis revealed that most conflicts and losses of separation occurred during the merging phase, where flights transitioned to their respective altitude levels. To tackle the challenge of merging conflicts, we then used insights from road traffic research and hence proposed two merge-assisting policies to reduce the onset of merging conflicts (see, Chapter 5). Based on the path towards achieving the research goal of this dissertation, we now reflect on the outcome of the research questions and present recommendations for future research.

6.2. RESEARCH QUESTIONS AND CONCLUSIONS

In Chapter 1, the main research objective of this dissertation was defined:

What design paradigms and methodologies from unconstrained airspace research and road transport infrastructure can be translated to a constrained urban airspace for high-density drone traffic operations?

In effort to address this guiding research question, we first broke it down into four sub-questions.

Q1. *What factors should be considered when estimating the potential traffic density culminating from drone-based delivery in a typical urban environment?*

The first research question was addressed in Chapter 2. The main starting point to determine the potential traffic density for delivery drones is the number of parcels per year for a particular country, as this data is broadly available. It is also important to use a set of valid assumptions to arrive at a reasonable estimate for the drone-based delivery volumes. For example, one particular assumption that we must be understandably cautious about is the number of operational days, that is, flight-time which is not hindered by ill-suited hyperlocal wind and precipitation events. Taking such influences into account, we developed a framework to compute the traffic density stemming from parcel delivery drones for a typical dense European city. Notably, our analysis also considered the popular notion of transporting fast-food meals via a fleet of autonomous delivery drones. We compared this urban delivery concept with electric bicycles, which are widely used across cities, especially in Europe and North America. Our analysis led to a discussion about delivery drones being a potential candidate for a sustainable transportation mode to support package delivery. Furthermore, the analysis unveiled that the demand for delivery of both small packages and fast-food meals via autonomous drones would cause the urban airspace to be highly populated with high traffic densities of drones.

The research performed in Chapter 2 developed three scenarios featuring conservative, high potential and high acceptability assumptions. With a conservative set of assumptions, we estimated a traffic density of almost 64,000 drone-based deliveries operating within an area of 12,012 km^2, which amounts to nearly 5 drones per km^2, in the city of Paris by 2035. Achieving such traffic volumes, however, depends on a host of factors, such as public acceptance, policy and regulations, and technical feasibility. Suffice it to note that the assumptions used to derive the traffic density estimates were performed at the early stages of this thesis. In retrospect, the policy frameworks and the technology capability are still in its research and developmental stage and hence much work remains to be done before such traffic volumes could manifest in urban areas by 2035. Yet, even if this time-line is prolonged, the estimated delivery drone traffic volume is more than six-fold greater than the global traffic volumes currently experienced in commercial aviation traffic and thus a robust airspace design will be required to safely accommodate such traffic volumes in dense urban areas.

Q2. *How can we use our knowledge from unconstrained airspace design and conventional road transport to design and structure the constrained urban airspace* *to safely harbour high densities of drone-based delivery traffic?*

In Chapter 2, our data showed that a typical city could potentially experience high traffic densities (4-5 drones per km^2) of commercial delivery drone operations. These probable scenarios will require an airspace configuration that is capable of accommodating large-scale traffic in a safe and efficient manner. Compared to conventional aviation, the challenge with operating autonomous drones in an urban environment is that the fact that it is heavily confined by a large number of man-made structures as well as the urban street network. To address this challenge, this study approached the problem from two perspectives. First, we looked at the current methods of traffic flow organisation and structuring in unconstrained airspace design. In particular, we examined the layers airspace concept that was proposed in the Metropolis project [184]. In that study, two principles were identified, namely, traffic segmentation and alignment, to mitigate conflict probability for high densities of traffic [89]. Second, to determine how we could apply traffic segmentation and alignment to a constrained environment, we examined how safety is achieved in road design for on-ground transport, which are confined to the same network as the streets. In road design, lanes are used to impose directional flow to create two-way and one-way traffic flows and hence, enable safe operations in urban streets [71, 72]. Therefore, the research in Chapter 2 explores the notion of flying over two-way and one-way streets in a way to structure and organise traffic flows in a constrained setting. Fundamentally, the two-way and one-way streets consist of traffic alignment and segmentation. In light of this, the work presented in Chapter 2, splits the above research question into two sub-research questions:

Q2.1. *To what extent can we apply traffic alignment and segmentation principles to a constrained urban airspace environment?*

Q2.2. *What is the performance of one-way and two-way airspace configurations with respect to safety, capacity and efficiency for high-density drone traffic?*

In unconstrained airspace design, both traffic segmentation and alignment is used to mitigate conflict probability. Hence, in Chapter 3, we applied the two principles to one particular highly-constrained urban environment, in a way to structure and organise the airspace. More specifically, to achieve this, we applied heading-altitude rules to the orthogonal urban street network of Manhattan, New York, to simulate traffic flow in a constrained environment. The heading-altitude rule was used to vertically segment the traffic according to the cardinal directions of north-south-east-west bound traffic headings and thus separating the competing traffic flows to different altitude layers. These rules and interventions were applied to the two-way and one-way airspace concepts.

Chapter 3, compares the performance of two-way and one-way airspace configuration with over 200,000 randomised origin-destination en-route flights, across three traffic demand levels. The two-way concept accommodates bi-directional traffic flow and thus opposing traffic is contained along the street, albeit in different altitude levels. While the one-way concept features uni-directional traffic flow and has twice as many vertical layers per allowed flight direction. To achieve a similar traffic distribution in the two-way concept, traffic is spread over different (parallel) streets. This horizontal distribution has the tendency to result in slightly higher number of turns per flight-plan. The analysis in Chapter 3 implies that the higher number of turns, associated with two-way concept, increases the total number of conflicts and intrusions. This increase is because of the larger number of merging events. The data presented in Chapter 3 therefore indicates the one-way concept to be better in terms of safety when compared to the two-way airspace configuration. Moreover, even though the one-way concept consisted of additional altitude bands in comparison to the two-way concept, both concepts demonstrated similar throughput and thus it means that having higher number altitude bands to harbour additional traffic per flight direction may not necessarily translate to higher means of throughput for the airspace. In summary, the study revealed that having both vertical segmentation of altitude layers to accommodate traffic with similar directions as well as horizontal constraints to promote uni-directional traffic flow, in constrained spaces, is beneficial for the safety of the airspace, especially in the case of high-density traffic of autonomous flying vehicles.

Q3. *What are the properties of conflicts and intrusions between the urban airspace design configurations?*

Chapter 4 investigates key properties of conflicts and intrusions of the one-way and two-way concept. In the analysis, we categorised and catalogued different types of conflicts and intrusions, namely, in-trail, crossing and head-on conflicts and intrusions for both level and transitioning flights. The investigation was performed on both airspace concepts across three traffic demand levels featuring thousands of flights. Interestingly, the data revealed that conflicts and intrusions were largely triggered during the merging phases, that is, flights which needed to climb and descend to their respective altitude layers. In these merging conflicts and intrusions, the majority were composed of in-trail and crossing conflicts in both airspace concepts, while merging conflicts in the two-way concept also consisted of head-on type conflicts, which was expected because of the enforced rules in the two-way airspace concept vertically separated the opposite traffic flows. In contrary, the structure of the one-way concept assumed opposite traffic flow to be laterally separated by the urban street network itself, which in turn eliminated the onset of head-on conflicts during the merging phase. The absence of head-on conflicts might have reduced the emergence of other types of conflicts to propagate throughout the network and thus making the one-way concept safer in terms of the total number of conflicts and intrusions, compared to the two-way concept.

Safely organising these merging flights in a highly constrained urban airspace is an enormous challenge. Road traffic design also copes with such complex merging problems within a high traffic demand setting. However, it took decades of research efforts to develop adequate solutions to address this problem [126]. In Chapter 4 we initiate a discussion in the pursuit of understanding why and how merging conflicts happen in the context of high-density drone delivery in constrained spaces.

Q4. *What emergent behaviour and patterns form when we impose rules and conditions to high-density drone traffic in a constrained urban area?*

It is broadly known that seemingly simple geometrical rules on an autonomous agent (drone), and its interaction with the environment can trigger undesired emergent behaviour [87, 199]. In effort to structure and organise the urban airspace to safely harbour high densities of drone traffic, we applied different rules and interventions. For instance, the heading-altitude rule and the spatial order of the urban street network was employed to impose traffic segmentation and alignment in the both airspace concepts. Consequently, these rules required flights to frequently climb and descend to their respective altitudes levels and therefore, as a consequence, it triggered conflicts and losses of separation in the merging phase.

To limit the onset of these merging conflicts and intrusions, we proposed two merge-assisting strategies, a delay-based and a speed-based strategy, in Chapter 5. These methods have been extensively tested in a number of road traffic engineering studies [71, 74, 109, 110, 158]. And since the operation of on-ground transport bears resemblance (to a certain extent) to that of drone traffic in constrained environments, it was therefore a reasonable assumption to also leverage this knowledge to our research.

In Chapter 5, we examined the performance of the merge-assisting strategies for the one-way airspace design concept across three traffic demand levels. Note that we chose the one-way airspace concept in this particular experiment because it ranked higher in terms of safety, when compared to the two-way airspace concept, as described in Chapter 4. After conducting our experiments, we analysed the data and found that both merge-assisting strategies showed a reduction of the total number of merging conflicts and intrusions. However, the efficacy of the strategies was much less than initially anticipated. To determine the cause, we explored key mesoscopic components of the network. The cause for the relatively low efficacy was attributed to disproportionately higher traffic density on specific streets of the urban network that resulted in insufficient space for safe manoeuvring of merging vehicles. Our results points to the specific routing scheme that optimised routes with respect to distance and thus channelling a larger number of traffic flow on certain 'popular' streets of the network, which resulted in high local traffic density; and the inability for the strategies to fully respond and thus resolve conflicts on short-distance streets..

The application of merge-assisting strategies to large-scale drone traffic is relatively new. Our exploration of on-ground transport methodologies in urban airspace science forms a basis for further exploration. We expect that it may open up new avenues for advanced air mobility research.

6.3. ADDITIONAL CONSIDERATIONS

In this section we discuss the main modelling assumptions used in each research chapter of this dissertation. Moreover, we discuss how this research can be extended to other forms of constrained spaces. Next, we initiate a discussion on combining the benefits of decentralised and centralised traffic management in effort to increase urban airspace safety.

6.3.1. MODELLING ASSUMPTIONS

To address the research questions posed in this dissertation, we employed the BlueSky flight simulator to perform fast-time simulations. To account for the dynamics and flight characteristics of drones, the tool was adapted to feature drone models and a relevant autopilot module. Since our research represents a first exploratory step towards structuring and organising a constrained urban area for high-density delivery drones; thus a number of assumptions were employed to reduce the complexity of our simulations.

IDEALISED CONDITIONS

In our experiments we simulated large-scale drone traffic for a scenario that projects far into the future of how urban delivery might unfold in cities. For this, many idealised conditions were used, which means that performance limiting factors and uncertainties, such as hyperlocal wind and precipitation, have been left out in the simulations.

Hyperlocal wind effects could considerably influence the trajectories of flights as well as airborne separation. Depending on the magnitude and direction of hyperlocal wind, drones could potentially explore such meteorological conditions to their advantage by aligning flight trajectories in a way to minimise headwinds and maximise tailwinds. A similar approach is used in current air traffic management in the North Atlantic Track system [193]. The result of exploring hyperlocal wind in cities could improve energy efficiency and lower travel times. For autonomous delivery drone operators that measures performance on the number of packages delivered per minute, which means that more packages can be delivered in less time and thus it would likely reduce the number of drones required for a particular fleet operator. Conversely, hyperlocal wind could also create local congestion hotspots by concentrating traffic to particular streets. Therefore, we advocate the use of a routing scheme that takes into consideration the direction and magnitude of hyperlocal wind. Similarly, hyperlocal wind could coerce drones to fly off-track and hence crash into obstacles, which would present as a major safety concern for third-party urban users. This means that there would be a strong need for accurate hyperlocal wind measurements in the future. Precipitation will also influence the traffic demand by restricting the proportion of safe ‘can-fly’ and ‘no-fly’ days. In Chapter 2, the effect of precipitation was accounted in the traffic density estimates for the experiments. With advancing technology, we assume that precipitation would play a minimal role on drones in the future.

EN-ROUTE FLIGHT PHASE

Our experiments only considered the en-route flight phases, while neglecting take-off and landing phases. Even though including the phases of take-off and landing would increase the real-world applicability of our simulations, we assume that in the future, delivery drones will mainly operate from vertiports or from under-utilised rooftops of skyscrapers that support the integration of drones in cities. Such concepts will reduce the need to climb and descend to areas that host many ground obstacles and hence minimise the risks associated with take-off and landings.

STATIC TRAFFIC DEMAND

Furthermore, the experiments presented in this thesis assumed traffic demand to remain static with time. This assumption does not hold well in real-world scenarios where demand is highly temporal in nature. It is likely that traffic demand in an urban airspace would have peaks and troughs, thus mimicking the types of traffic patterns seen in existing transport modes in cities. This also means that there would be specific locations that exhibit a disproportionately higher demand than other parts of the network. Such patterns have emerged in car-sharing studies, where demand for the service is primarily driven by particular events [7, 130]. In fact, in Chapter 5, the data showed similar evidence of hotspot locations for which traffic demand in specific streets was higher, largely because of the employed routing scheme and its associated assumptions. Yet, though the routing assumptions aimed to simplify the simulations even with idealised conditions, the emergence of traffic hotspots in the network can be generalised to how traffic patterns arise in real-world networks.

STATE-BASED CONFLICT DETECTION

The research presented in Chapters 3 to 5 employed a state-based conflict detection method that was initially built for current manned air traffic research. The conflict detection method linearly extrapolates the drones' state within a prescribed look-ahead time. As a consequence, it has the tendency to trigger false conflicts, which may limit the overall safety of the airspace. In our experiments, a higher number of false conflicts were triggered in response to a larger look-ahead time (30 *s*), compared to a smaller look-ahead time of 10 *s* that triggered fewer false conflicts. With larger look-ahead times, the state of the aircraft was extrapolated to portions of the airspace that was not even in the flight-plan. To a certain extent, such observations are also experienced in road traffic where drivers are encouraged to anticipate certain traffic situations and thus react accordingly. Similarly, our research employed a look-ahead time that remained constant with traffic density. When compared to road vehicles, a look-ahead time might reflect the current state of the traffic, for example, in congested traffic the look-ahead time could be assumed to be smaller compared to the free-flow traffic state. Therefore, by assuming a fixed look-ahead time, the number of conflicts measured in our experiments may have been overestimated.

FIXED SEPARATION MARGIN

This research assumed a fixed separation margin. In road traffic, drivers and advanced adaptive cruise control systems utilise a dynamic approach to estimate a safe horizontal separation margin. This horizontal separation margin is a function of the distance to the leading vehicle and the speed of the following vehicle. Hence, the horizontal separation distance varies with traffic density. For example, the separation distance is larger when cruising on the highway and it is assumed to adapt to the traffic density and thus reduce, for instance, when exiting the highway from the merge lane. In this context, vehicles are allowed to be in close proximity to each other and still ensure a relatively high-level of safety. This allows for higher capacity and safety. Therefore, the constant separation margin used in the study does not represent real-world conditions and thus it may limit the capacity of the network.

6.3.2. DISTRIBUTED CONTROL AND CENTRALISED CAPACITY MANAGEMENT

In this thesis, conflict management is supported by the airspace structure and the tactical airborne separation algorithm. The airspace structure is assumed to increase the intrinsic safety of the airspace and thus prevent any unnecessary conflicts being triggered by incorporating traffic segmentation and alignment. While the tactical airborne separation algorithm is tasked with resolving any ad-hoc and sudden conflicts that may arise. Since this research assumes high traffic densities, the two pronged conflict management approach allows for fast and efficient de-confliction rates. This paradigm of conflict management can be compared to how safety is guaranteed in road traffic. Roads and highways maintain a level of safety by having channelisation planes and dedicated lanes to facilitate traffic segmentation and alignment, while separation is distributed to each individual vehicle [38, 71, 87]. However, road traffic does have an additional layer of safety to manage traffic capacity, especially on the highways where ramp metering is predominately used during peak times to control the inflow of traffic entering the mainline [108]. Adopting a similar methodology for traffic management of advanced air mobility concepts would not only support the flexibility of the airspace, but it could also foster the scalability that is required by express package delivery operators.

Instead, advanced air mobility traffic management programs, such as U-Space, offer an alternative approach. For example, policymakers are advocating conflict management that is more inclined towards strategic planning and flight-plan de-confliction [15], which consist of filing individual flight-plans for each and every flight and seeking approval. We foresee two challenges here. First, is the lack of flexibility, which is required by its users. Second, such centralised flight-plan de-confliction methods scale quadratically with traffic and thus cause delays, especially in approving individual flight-plans [87]. Any delays caused by the approval of flight-plans would render such novel delivery modes infeasible and less attractive for operators. To support this emerging ecosystem, policymakers would need to prioritise service-flexibility and thus foster the use of distributed airborne separation, airspace design and traffic capacity management.

6.3.3. EXTENSION TO OTHER CONSTRAINED ENVIRONMENTS

OTHER OUTDOOR ENVIRONMENTS

The methods and findings presented in this thesis have focused on constrained environments featuring an orthogonal urban network, such as Manhattan, New York city. This grid-like network was chosen because of its spatial order, specifically, the fewer number of dead-ends, more four-way intersections and less-winding street patterns [29], which does not skew the generalisability of our findings. Furthermore, such orthogonal networks represent a large portion in newly developed street networks, globally [30, 75]. However, there still exist seven other types of street networks which are typically found in many European cities, such as, for example, Paris, Amsterdam or Vienna. Any attempt to adapt the methods proposed in this thesis to non-orthogonal street networks should examine how the imposed constraints of the airspace design influence traffic segmentation and alignment of traffic flow. In line with this context, research has already begun applying and investigating the methods and findings proposed in this thesis to non-orthogonal grid networks [13].

INDOOR ENVIRONMENTS

Even though a broad array of use-cases exists for outdoor drone applications, there is also, however, considerably high interest placed on employing autonomous drones in constrained indoor areas, for example, in large-scale warehouses and manufacturing plants [42, 204]. These autonomous drones could play a vital role in the inspection of inventory and transporting of small packages within this indoor environment. Such indoor spaces are heavily populated with obstacles and hence, organising and structuring flight routes is crucial for safe operations. Assuming warehouse aisles and shelves are organised to support one-way traffic flow [146], we thus advocate the use of our methods proposed in this thesis in effort to organise and structure the indoor space for future drone traffic. In addition, prospective delivery drone operators, such as Amazon could also use their warehouses as test-beds, in a way to transition to outdoor delivery operations.

6.4. Recommendations for future research

This thesis addressed the challenge of designing urban airspace concepts for high traffic densities of package delivery drones by learning from the design methodologies used in unconstrained airspace research and road transport infrastructure. As discussed in Section 6.3.1, assumptions were made to scope the research and to be within the time and resource limits. As the first step towards a constrained urban airspace design, this thesis contributed to several novel insights on how to safely harbour high densities of drone-based delivery traffic in urban spaces. However, answering scientific questions always unveils newer and more intriguing questions. Here, we present a few main recommendations for future avenues of research to further broaden our understanding of the subject.

6.4.1. Direction for conflict detection research

The findings presented in this dissertation indicated that the conflict detection method triggered false conflicts. This was because the conflict detection linearly extrapolated the drones' state within a fixed look-ahead time. To reduce the onset of false conflicts, we recommend incorporating intent information. As discussed in Section 6.3.1, future research should investigate the notion of dynamic look-ahead times and separation margins, which conform to the traffic conditions.

6.4.2. Towards addressing the merging problem

More work and research focusing on understanding the merging problem for autonomous drones in a constrained urban setting is required. Even for road traffic research, the merging problem still remains to be a challenge, especially for automated cars [123]. The research presented in Chapter 5 highlighted some of the open questions that needs more attention in the future. The process of merging involves a great deal of coordination of state and intent information between a host of actors. In manual driving scenarios, a safe merging event is preceded by social ques, commonsense and ethical considerations that serve as input to the decision process. This is obviously difficult to program into a autonomous vehicle. As a step forward, future work should investigate an optimal merging strategy that involves multiple levels of safety, which includes a traffic flow metering strategy, in addition to the strategies presented in Chapter 5.

6.5. KEY FACTORS FOR POSITIVE SOCIETAL IMPACT

The use of drones to transport goods and people is an eminently practical approach that is receiving growing attention. However, similar to automated cars and other micro-mobility vehicles, the societal impact of drones will be largely sculpted by the right policies, public acceptance and trust, and technical feasibility.

6.5.1. POLICY DECISIONS

Faced with the demand for quick and easy last-mile travel, cities are now struggling to cope with the advent of micro-mobility vehicles, such as electric cargo bicycles and stand-up scooters. Compared to their advantages of being clean and producing zero-emissions, the improper organisation and ad-hoc policies have also highlighted the many drawbacks of these transport modes [91]. As a result, they now represent a major safety hazard for urbanites and thus pose as a nuisance rather than a blessing. Delivery drones might meet the same fate if the correct policies and regulations that foster safe traffic organisation are not adopted in time.

6.5.2. PUBLIC ACCEPTANCE AND TRUST

Public acceptance and trust is essential for realising the benefits of autonomous delivery drones. The perspective on what is a nuisance than when it is available has largely been demonstrated across history [73]. For instance, people initially regarded smartphones as a nuisance than a convenient tool. This is because humans are notoriously bad at envisioning the benefits of technology until they see it for themselves. The basis of how the general public judges the value of such innovation is predominately influenced by their perception of how much transparency is offered by the manufacture and testing authorities, the ethical considerations and ultimately the science communication [45]. More often, the general public is made aware of emerging technology through the lens of legal proceedings associated with failures [79], or via media discourse [177], or in social networks, which has a tendency to distort information [167]. A well-informed society is crucial for making rational decisions, especially future referendums that support autonomous flying robots or even automated cars. Public acceptance and trust can only be realised by clearly communicating the scientific understanding of the concerns at issue [167].

6.5.3. TECHNICAL FEASIBILITY

Besides ethical concerns and safety issues [165, 186], there are some technical hurdles that are yet to be solved. For instance, multicopter drones generate incessant buzzing noise, which needs to be addressed by designers. A typical commercial delivery drone could have a noise level of more than 90dB, which is more than a gas-powered lawn mower [140]. Being exposed to such annoying noise levels for prolonged time periods may lead to hearing damage or other types of health concerns. Hence, if multicopter delivery drones were to gain public acceptance and hence operate in our cities, the current technology of propellers would need to be redesigned.

This dissertation sheds light on a path towards safely accommodating high densities of drone-based delivery traffic in constrained urban environments. Although the research presented here focused on delivery drones, the methods could also be applicable towards other advanced air mobility concepts, for instance, passenger drones or flying taxis. There is a broad scope for autonomous flying entities, or any other flying robots that may evolve in the future, in our cities. Yet, I remain cautiously optimistic. Unbridled optimism is unwarranted in a world where historically, humans have only adopted sufficient safety measures and guidelines after the occurrence of an accident. Therefore, it is imperative that policymakers and designers develop adequate policies and resolutions to ensure that drones operate in a safe manner while respecting the privacy and well-being of not only humans but also all other forms of occupants of the urban airspace as well as conserving the beauty of nature.

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2011 – 2014 Bachelor of Science, Aerospace Engineering
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2010 – 2011 Bachelor of Science, Aeronautical Engineering
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EXPERIENCE

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2018 – 2022	PhD Candidate, TU Delft Delft, The Netherlands
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2015 – 2015	Junior Consultant (Intern), Deerns Airport Consultancy Rijswijk, The Netherlands
2011 – 2011	Aircraft Engineer (Intern), Sri Lankan Airlines Colombo, Sri Lanka

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